High frequency gravitational waves in axion experiments

17th Patras Workshop on Axions, WIMPs and WISPs

Mainz, Germany
Aug 11, 2022

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

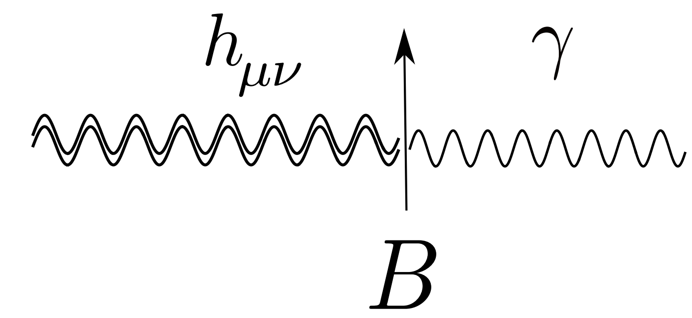
Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

Novel Search for High-Frequency Gravitational Waves with Low-Mass Axion Haloscopes

Valerie Domcke, Camilo Garcia-Cely, and Nicholas L. Rodd
Phys. Rev. Lett. **129**, 041101 – Published 20 July 2022

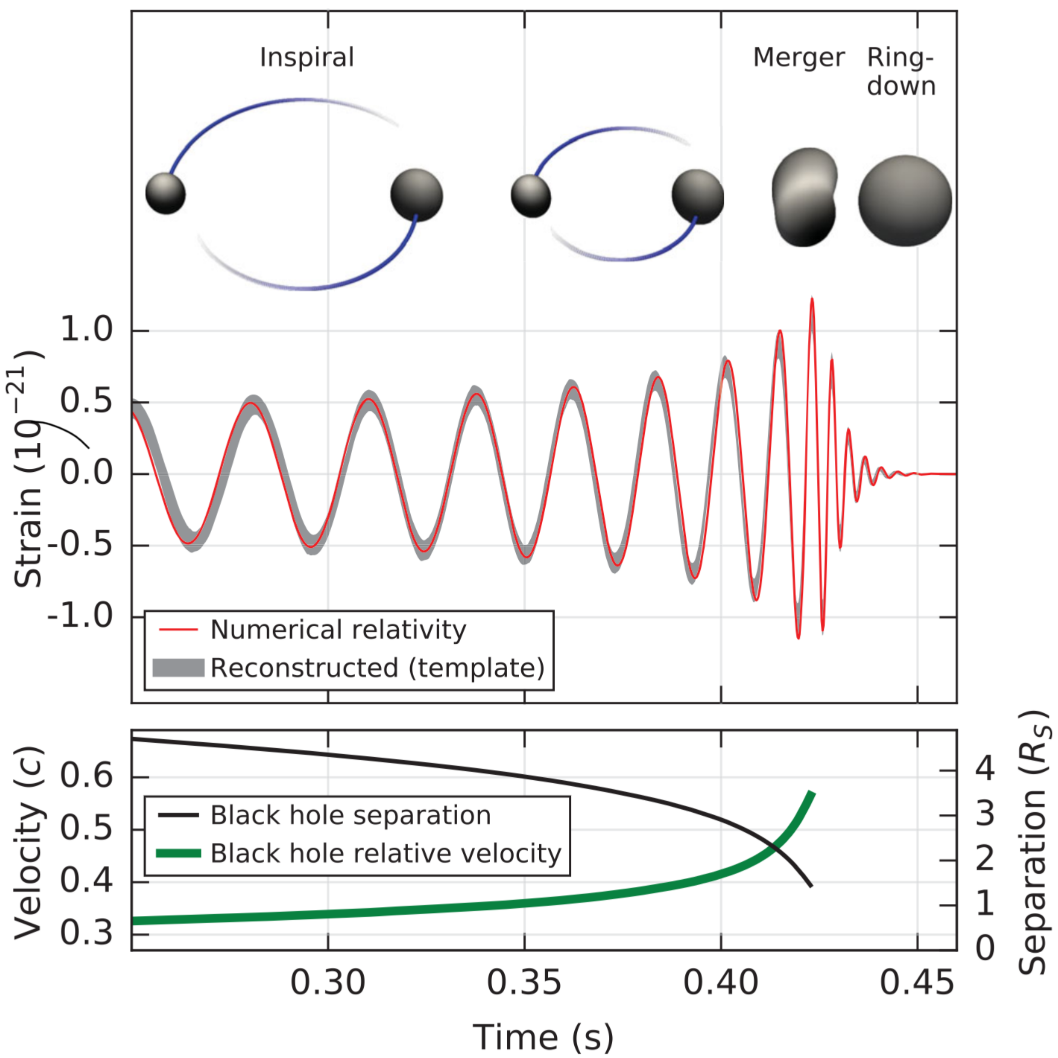
Outline



- Motivation
- Gravitational-wave versus axion electrodynamics
- Detection at laboratories (cavities, lumped element detectors, etc.)
- Cosmological detectors
- Conclusions

Motivation

High-frequency gravitational waves



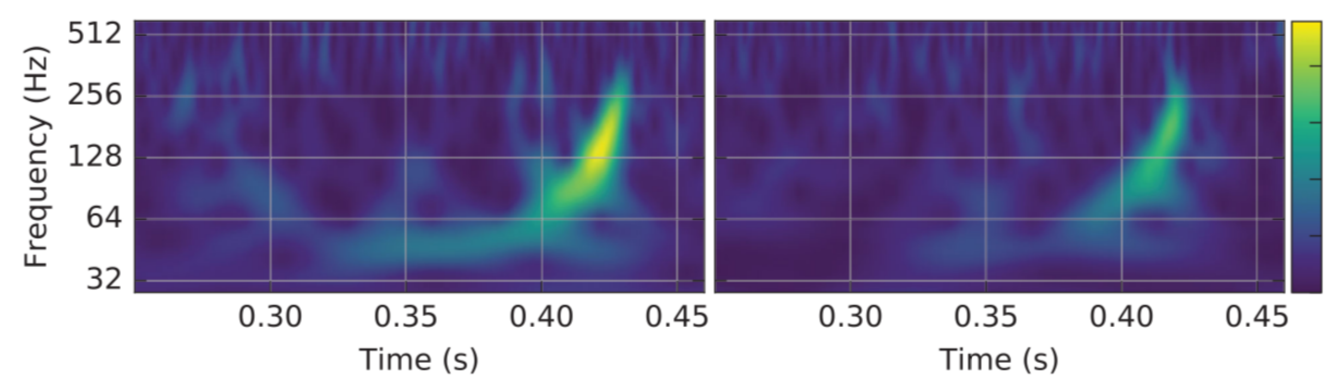
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



$$f \ll 10\,\text{kHz}$$

There are no known astrophysical objects that are small and dense enough to produce gravitational waves beyond 10 kHz

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High-frequency gravitational waves

Part of a collection:

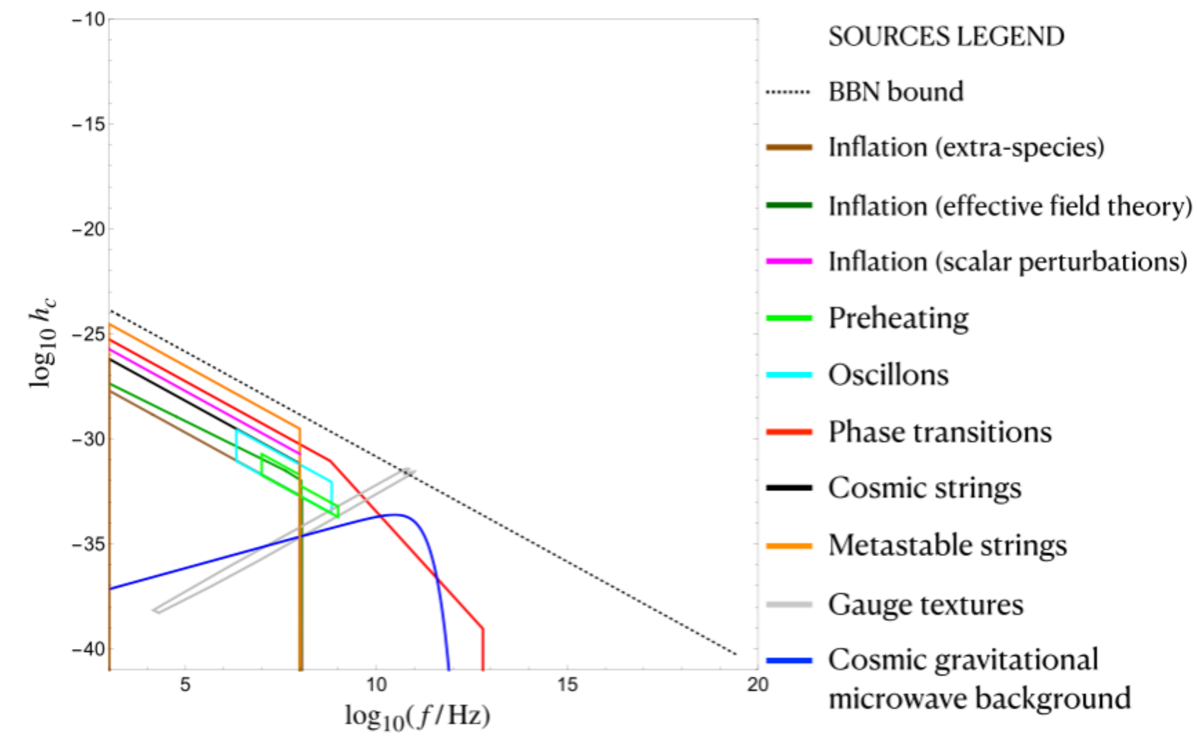
Gravitational Waves

Review Article | Open Access | Published: 06 December 2021

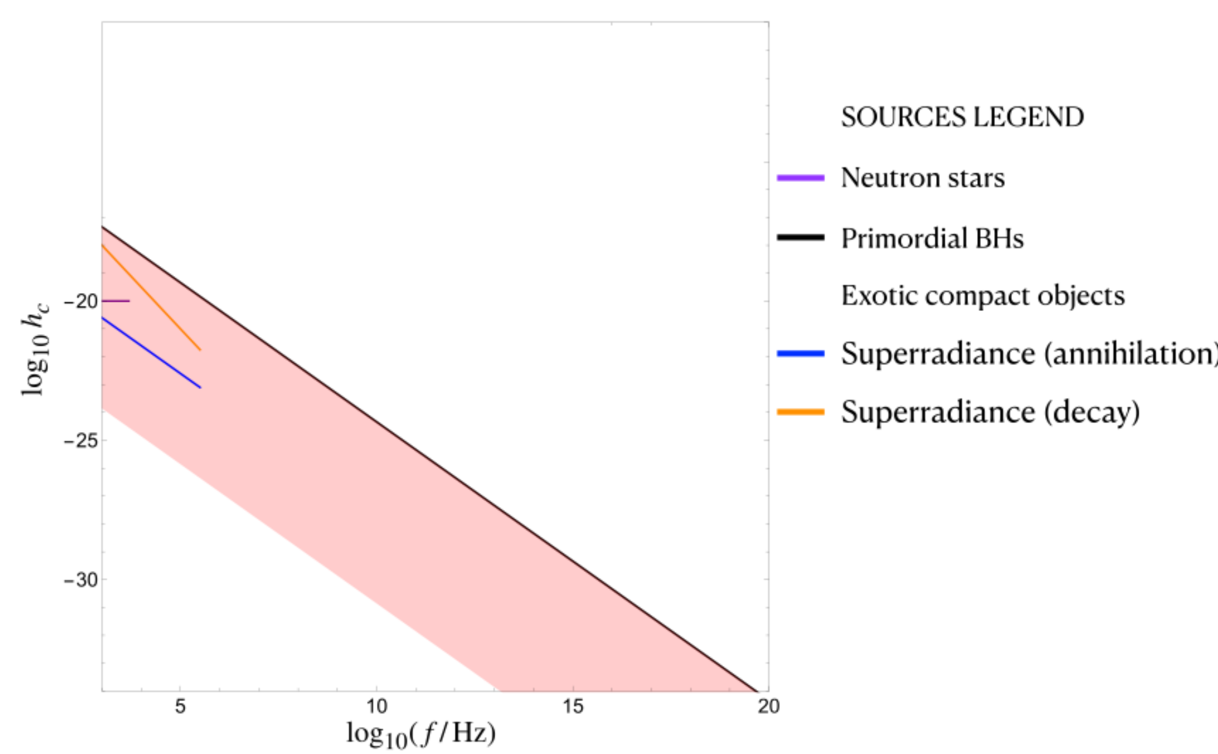
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

Nancy Aggarwal, Odylio D. Aguiar, Andreas Bauswein, Giancarlo Cella, Sebastian Clesse, Adrian Michael Cruise, Valerie Domcke, Daniel G. Figueroa, Andrew Geraci, Maxim Goryachev, Hartmut Grote, Mark Hindmarsh, Francesco Muia, Nikhil Mukund, David Ottaway, Marco Peloso, Fernando Quevedo, Angelo Ricciardone, Jessica Steinlechner, Sebastian Steinlechner, Sichun Sun, Michael E. Tobar, Francisco Torrenti, Caner Ünal & Graham White

Living Reviews in Relativity **24**, Article number: 4 (2021) | Cite this article



A growing community is seriously considering the search of high frequency gravitational waves



Gravitational-wave versus axion electrodynamics

Axion electrodynamics

Axions act as a source term to Maxwell's equations, effectively inducing an electromagnetic current.

$$\nabla \cdot \mathbf{B} = 0$$

Sikivie, 1983

$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = j^0$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{j}$$

$$j^0 = -\, g_{a\gamma\gamma} \nabla a \cdot \mathbf{B} \qquad \mathbf{j} = g_{a\gamma\gamma} \left(\nabla a \times \mathbf{E} + \partial_t a \mathbf{B} \right)$$

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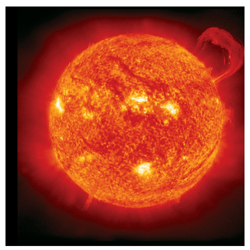
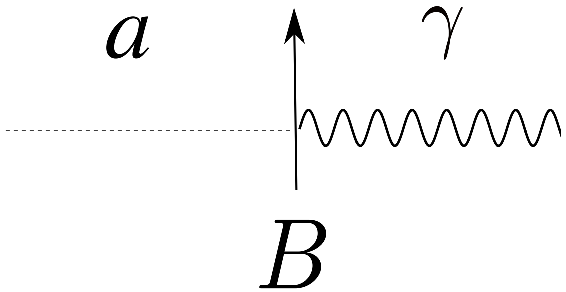
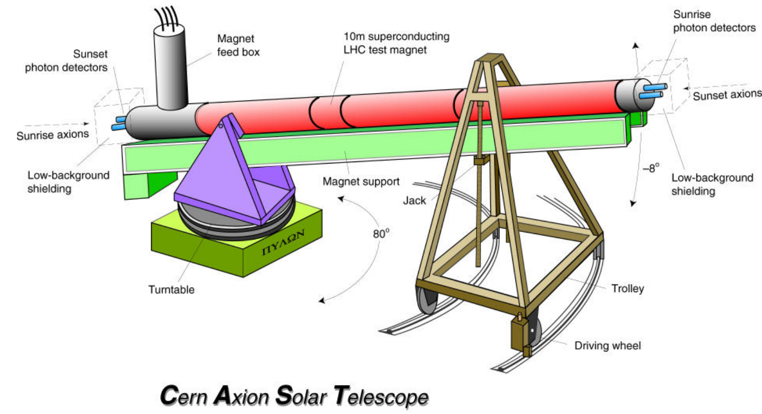
Axion electrodynamics

- Helioscopes (X rays)

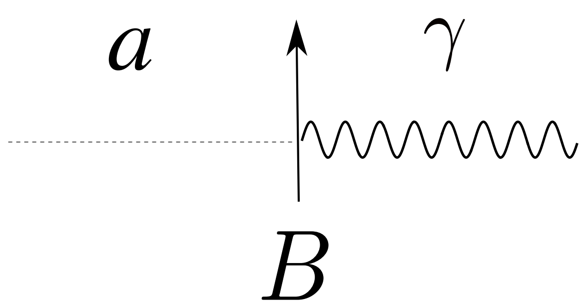


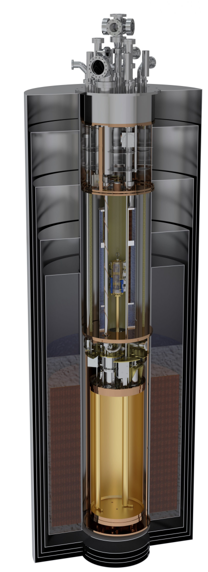




- CAST
- IAXO
- .....

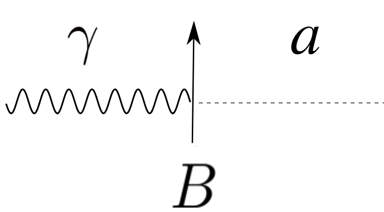
- Haloscopes (radio frequencies)

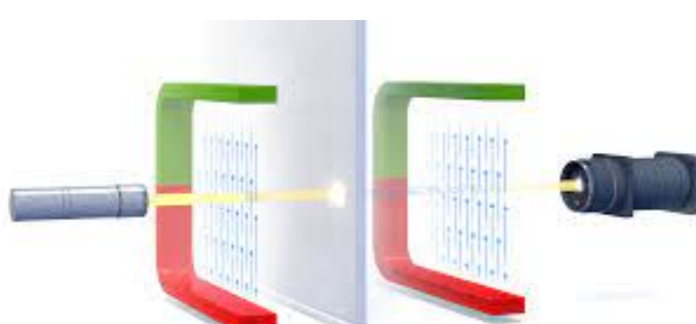


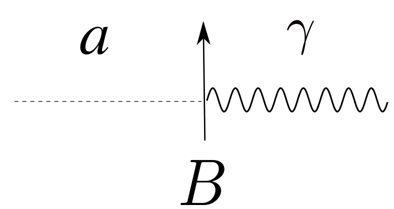


- microwave cavities
- MADMAX
- ADMX
- HAYSTAC
- ABRACADABRA
- Lumped element detectors
- ...

- Purely lab experiments







- Light shining through the walls
- OSCAR
- ALPS II
- ...

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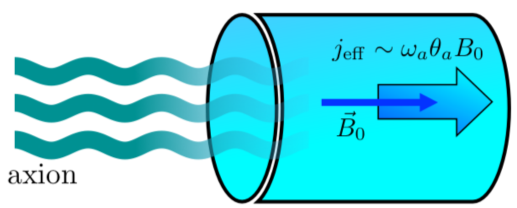
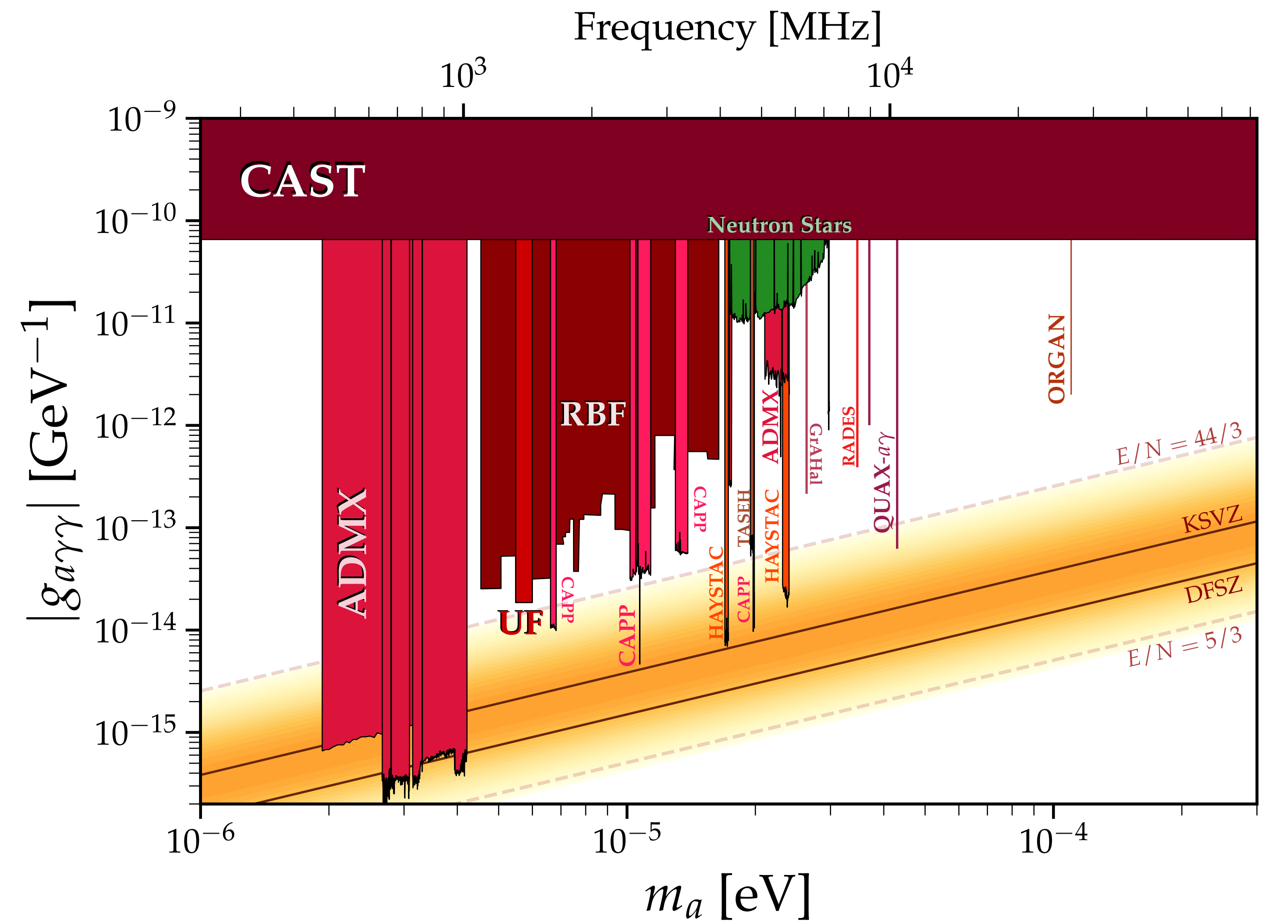
Haloscopes based on microwave cavities





https://github.com/cajohare/AxionLimits

It resonates when the axion frequency matches one of the eigenmode frequencies

$$\left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right) e_n(t) = -\frac{\int_{V_{\rm cav}} d^3\mathbf{x}\,\mathbf{E}_n^* \cdot \partial_t \boldsymbol{j}_{\rm eff}}{\int_{V_{\rm cav}} d^3\mathbf{x}\,\left|\mathbf{E}_n\right|^2}$$

Eigenmodes $\mathbf{E}(\mathbf{x}, t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$

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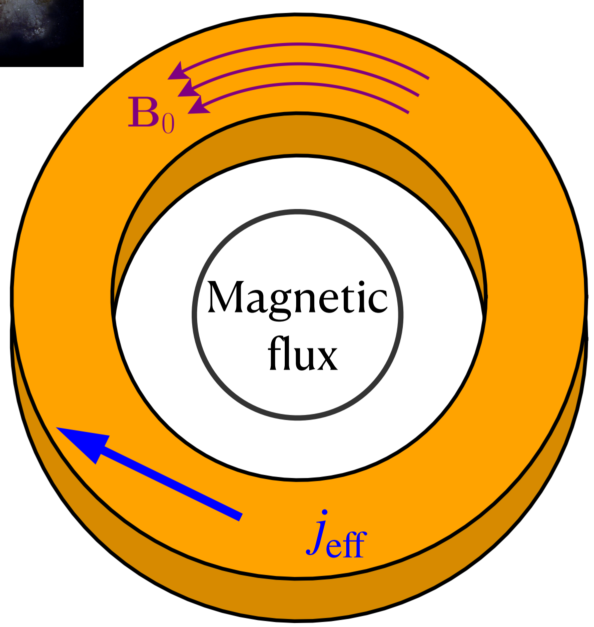
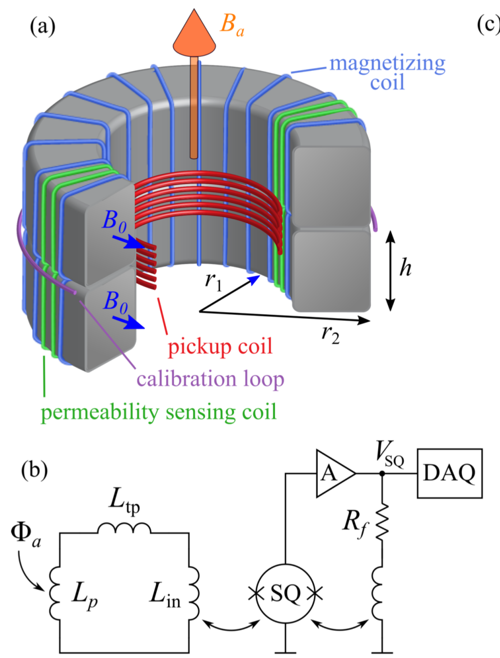
Haloscopes based on lumped-element detectors





(c) SHAFT

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \underbrace{g_{a\gamma\gamma}\, \partial_t a\, \mathbf{B_0}}_{j_{\rm eff}}$$

physics https://doi.org/

Search for axion-like dark matter with ferromagnets

Alexander V. Gramolin[1], Deniz Aybas[1,2], Dorian Johnson[1], Janos Adam[1] and Alexander O. Sushkov[1,2,3]

PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]

[1]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*

[2]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 3 March 2016; published 30 September 2016)

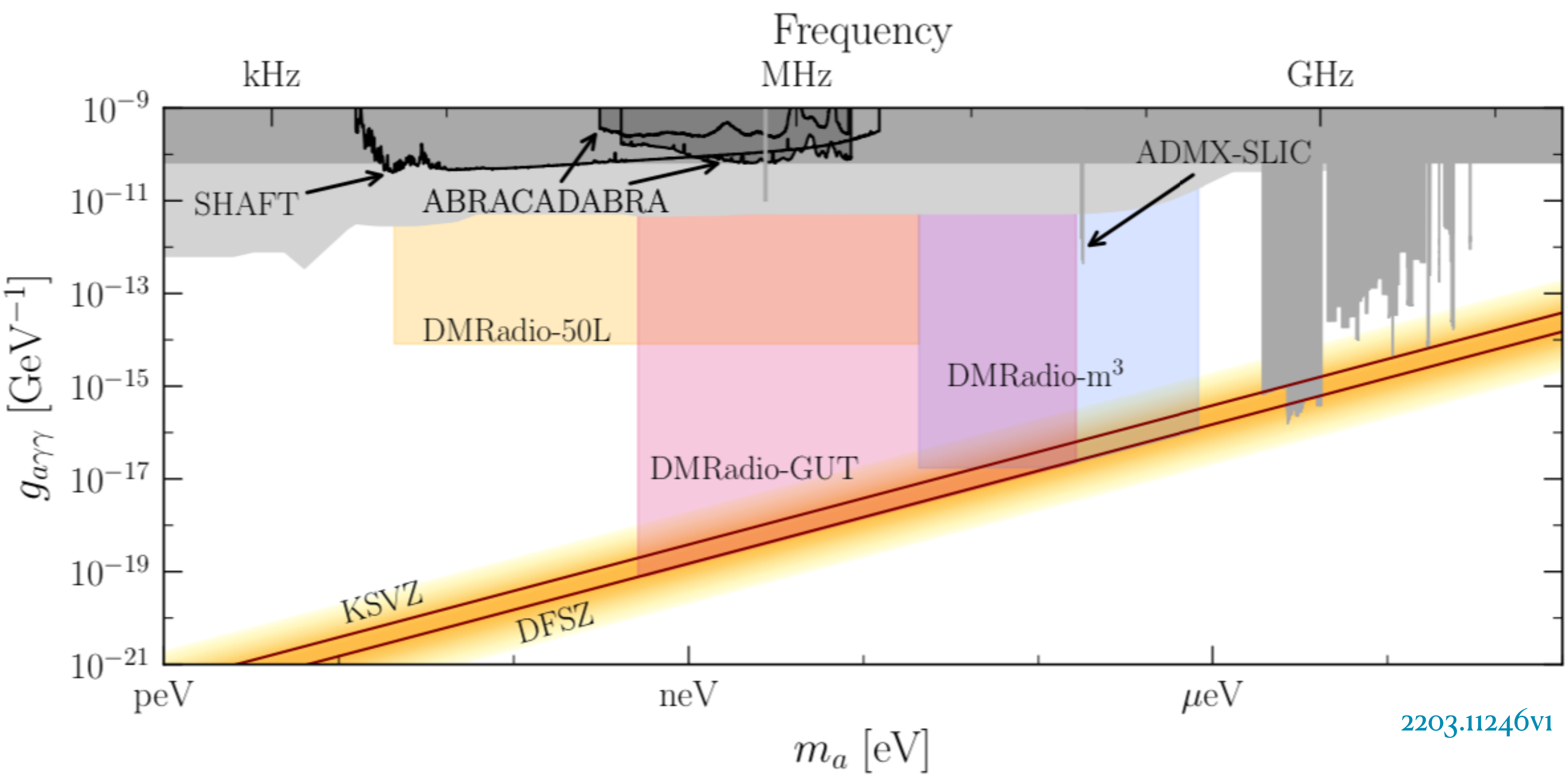
The electromagneticfields produced by the axion drive a current through a pickup coil

Searches at frequencies lower than those achieved with conventional cavity haloscopes.

Kahn, Safdi, Thaler 2016
Sikivie, Sullivan and Tanner 2014

DMRadio program

Searches at frequencies lower than those achieved with conventional cavity haloscopes.



2203.11246v1

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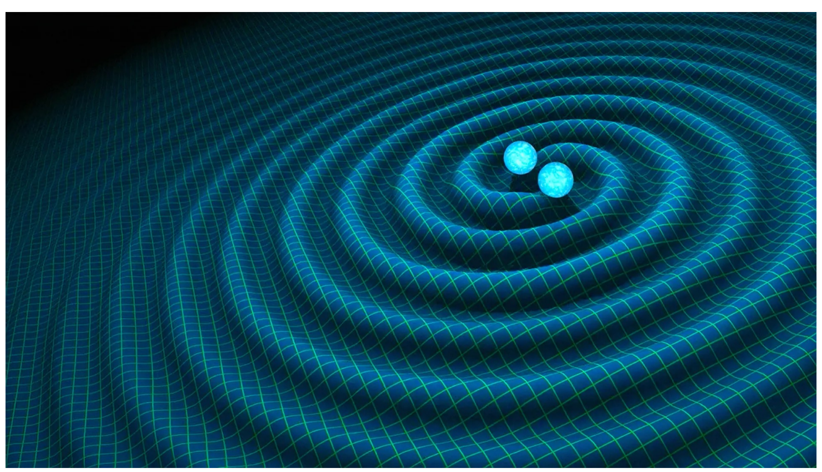
Effective current for gravitational waves

Gravitational waves act as a source term to Maxwell's equations, effectively inducing an electromagnetic current.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left| h_{\mu\nu} \right| \ll 1$$



$$j^{\mu}_{\text{eff}} = \partial_{\nu} \left(-\frac{1}{2} h \, F^{\mu\nu} + F^{\mu\alpha} h^{\nu}{}_{\alpha} - F^{\nu\alpha} h^{\mu}{}_{\alpha} \right)$$

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Detection at laboratories

The (inverse) Gertsenhstein Effect

SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962

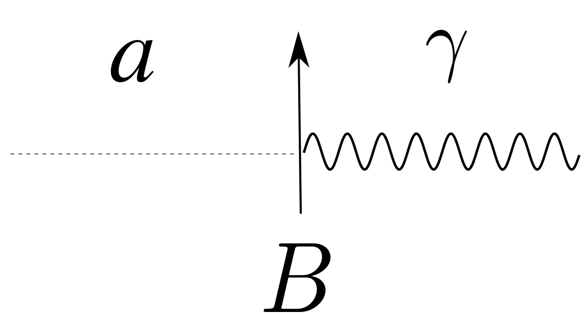
WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

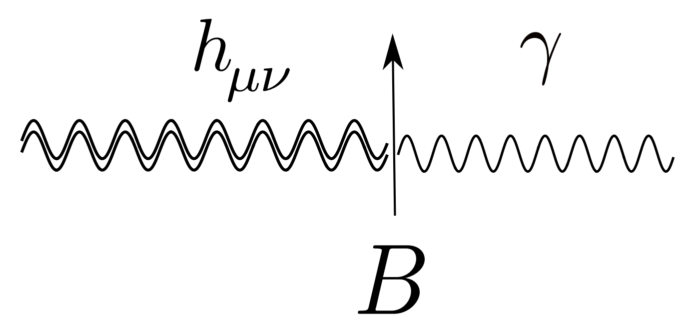
M. E. GERTSENSHTEĬN

Submitted to JETP editor July 29, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113-114 (July, 1961)

The energy of gravitational waves excited during the propagation of light in a constant magnetic or electric field is estimated.





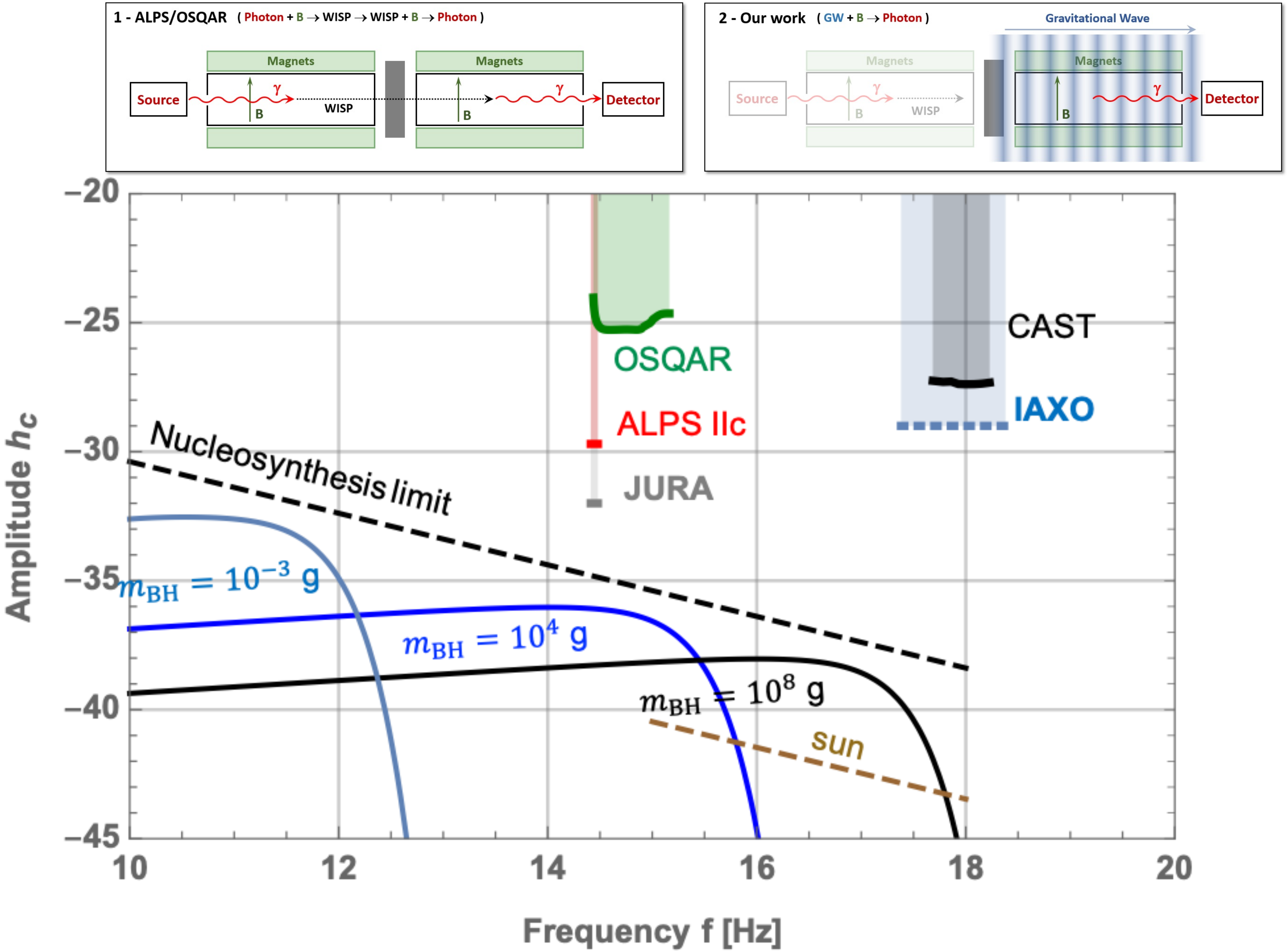
Raffelt, Stodolski'89

Ideas and techniques developed for axions can be adapted to gravitational waves

Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

The European Physical Journal C **79**, Article number: 1032 (2019)



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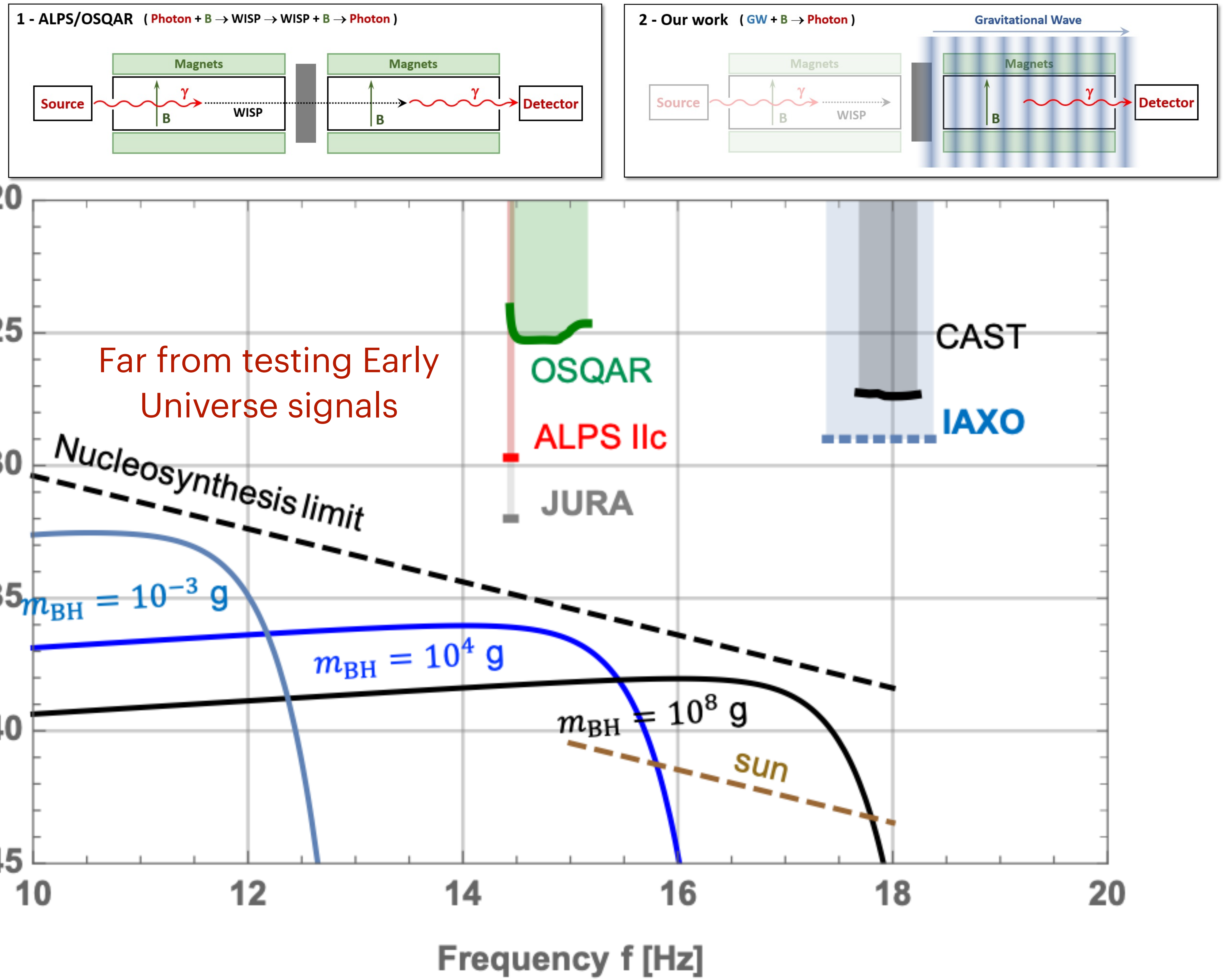
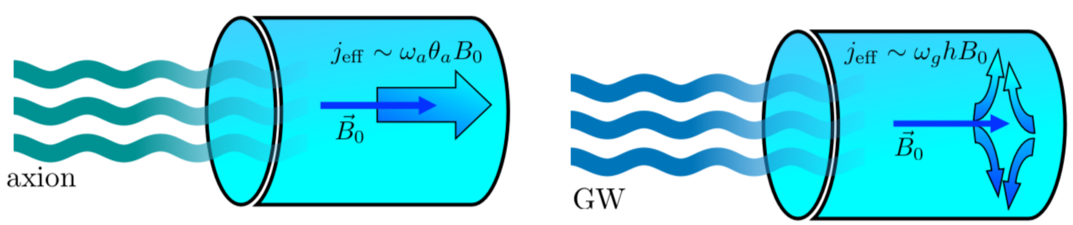


Haloscopes based on microwave cavities

Detecting High-Frequency Gravitational Waves with Microwave Cavities

Asher Berlin (New York U. and Fermilab), Diego Blas (Barcelona, Autonoma U. and Barcelona, IFAE), Raffaele Tito D'Agnolo (IPhT, Saclay), Sebastian A.R. Ellis (U. Geneva (main) and IPhT, Saclay), Roni Harnik (Fermilab) et al. (Dec 21, 2021)

e-Print: 2112.11465 [hep-ph]



It resonates when the GW frequency matches one of the eigenmode frequencies

$$\left(\partial_t^2 + \frac{\omega_n}{Q_n}\partial_t + \omega_n^2\right) e_n(t) = -\frac{\int_{V_{\rm cav}} d^3\mathbf{x}\mathbf{E}_n^* \cdot \partial_t \boldsymbol{j}_{\rm eff}}{\int_{V_{\rm cav}} d^3\mathbf{x} \left|\mathbf{E}_n\right|^2}$$

Eigenmodes $\mathbf{E}(\mathbf{x}, t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$

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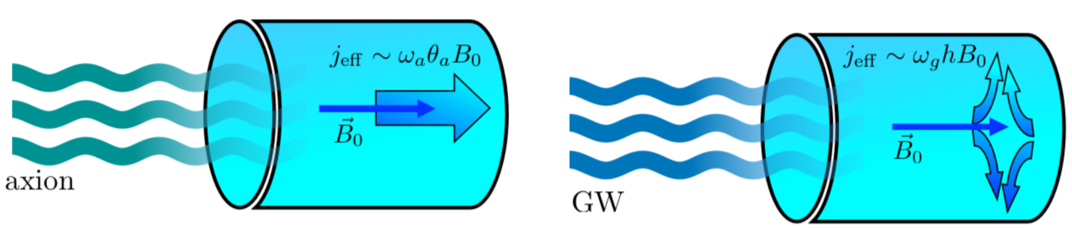

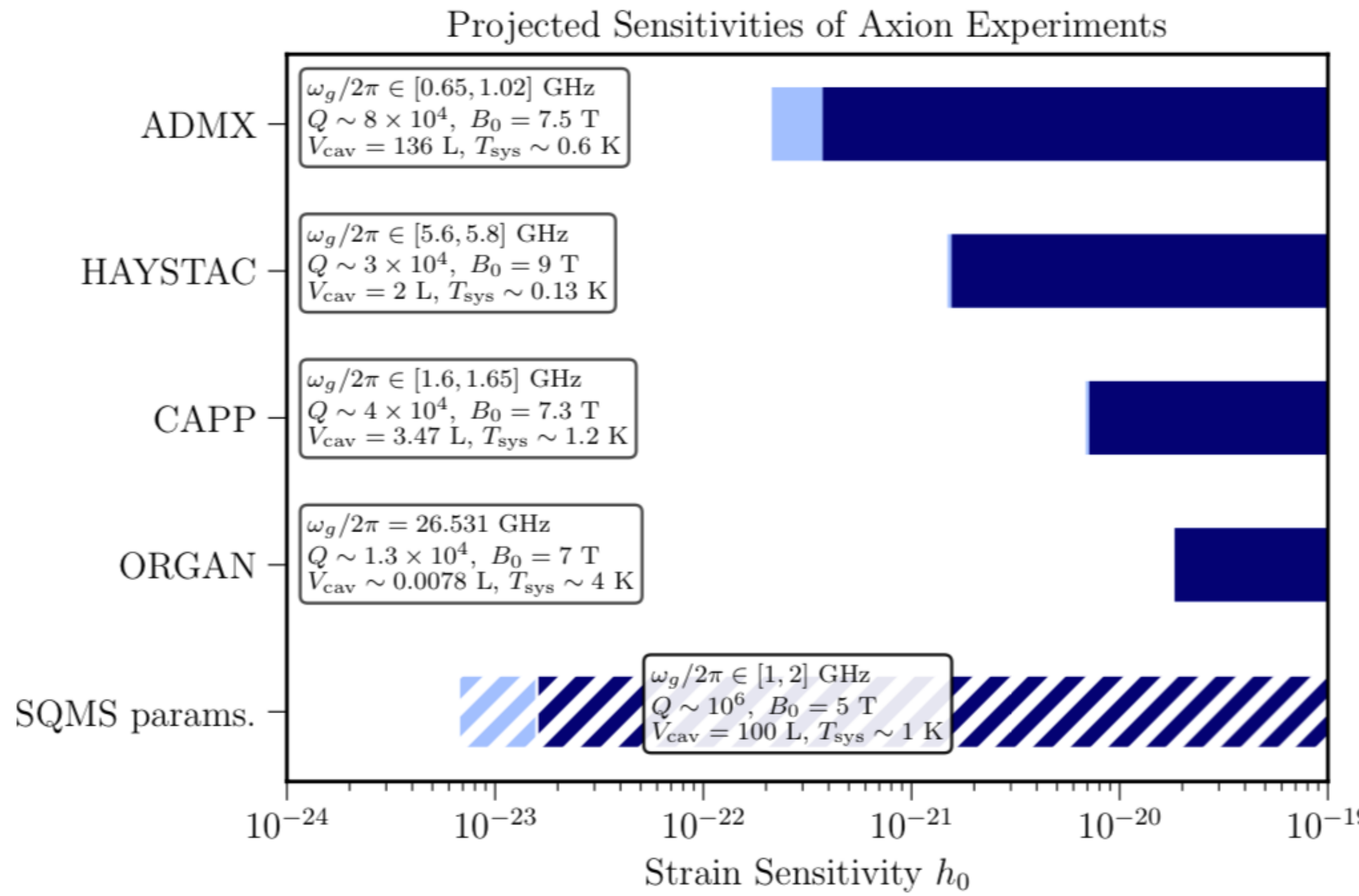

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Eigenmodes

$$\mathbf{E}(\mathbf{x}, t) = \sum_n e_n(t)\mathbf{E}_n(\mathbf{x})$$

Subtleties due to gauge fixing (TT vs detector frame gauge)

Detecting High-Frequency Gravitational Waves with Microwave Cavities

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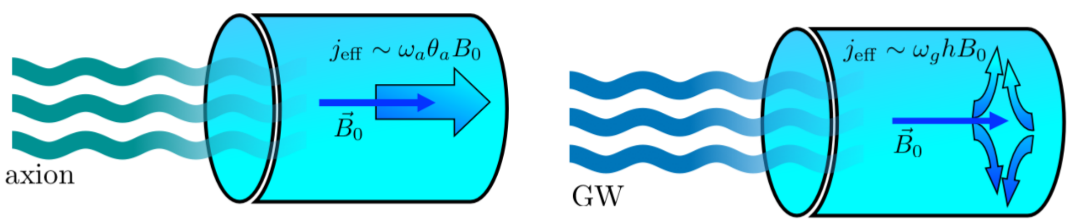
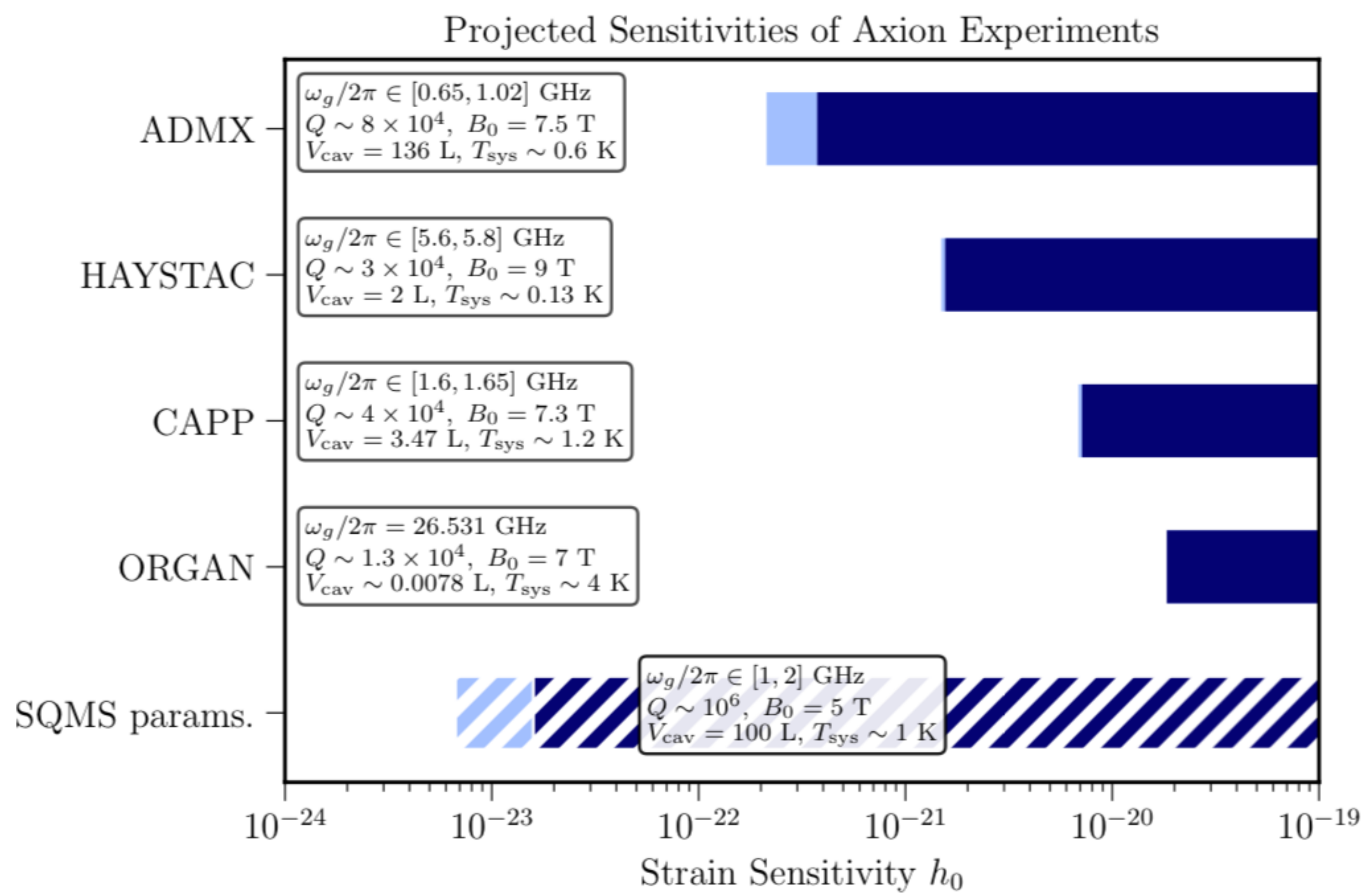
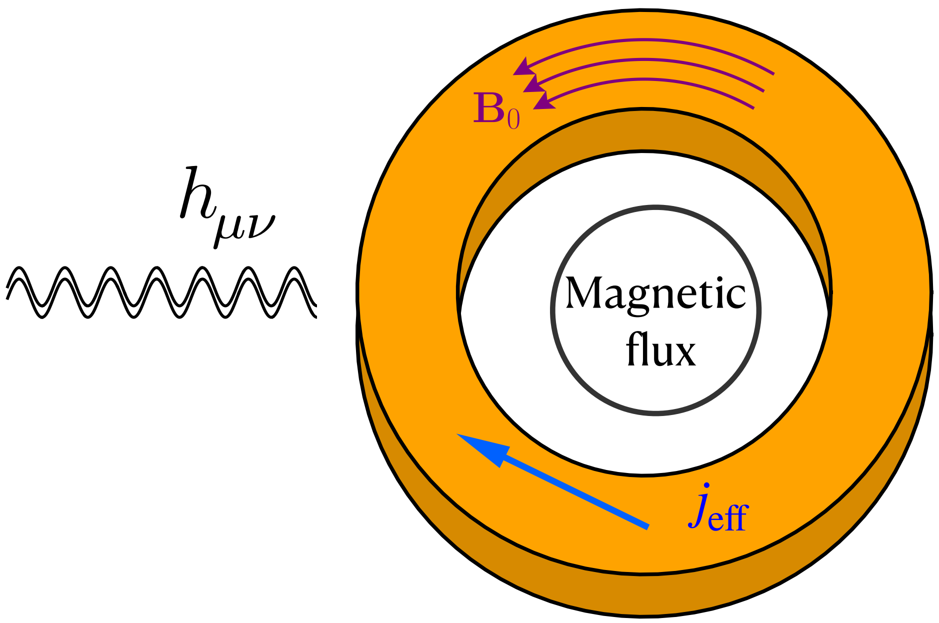


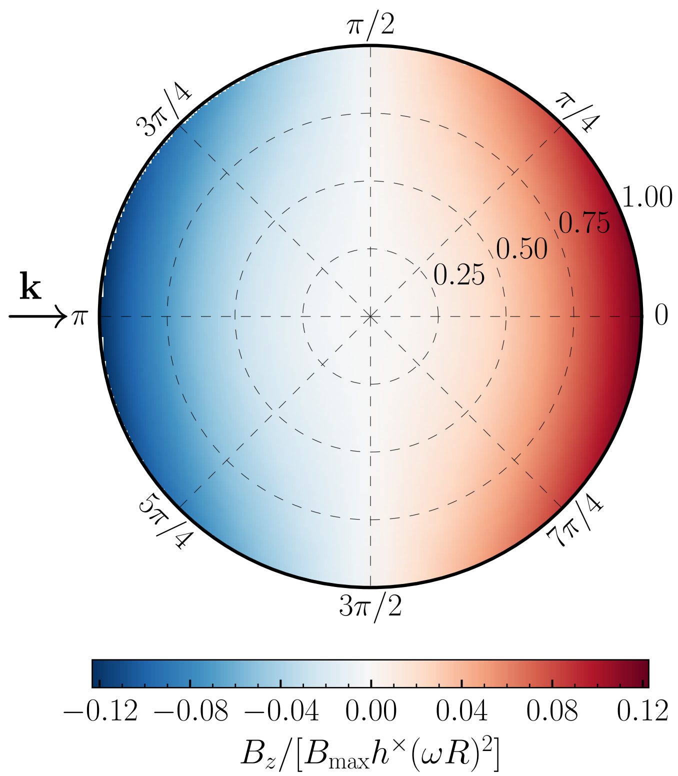


- In the TT frame, the description of rigid bodies becomes unintuitive, as their coordinates are deformed by a passing GW due to the motion of the coordinate system. **This is crucial to implement boundary conditions.**
- In the proper detector frame the coordinate system is defined by rigid rulers and closely matches the intuitive description of an Earth-based laboratory, with the GW acting as a Newtonian force.
- Previous confusion in the literature due to this (see e.g. 2012.12189)

Haloscopes based on lumped-element detectors

Domcke, CGC, Rodd, 2202.00695





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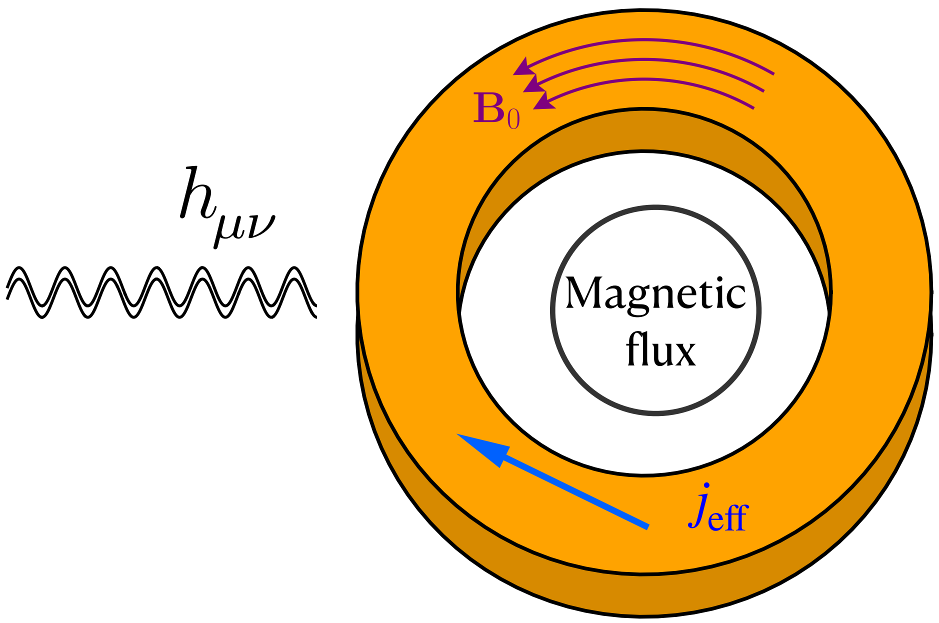
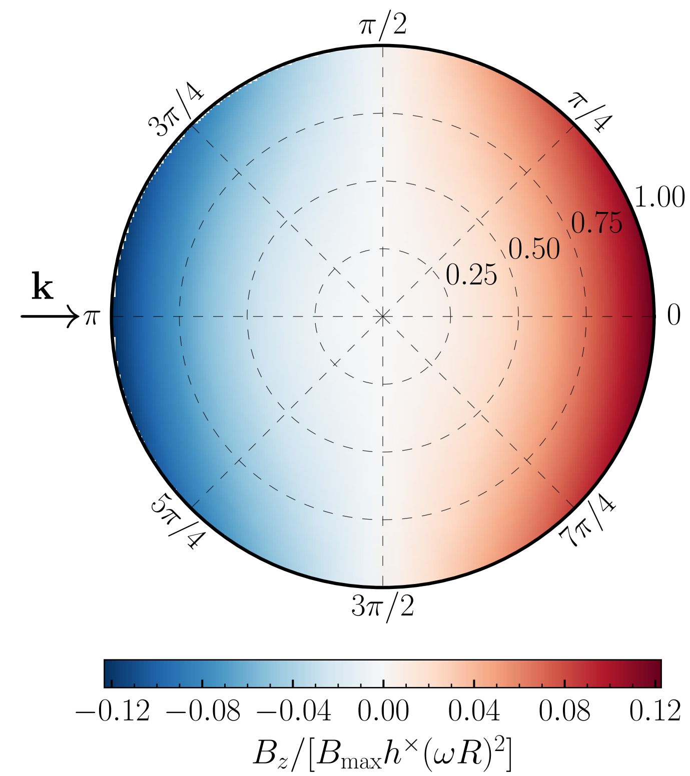




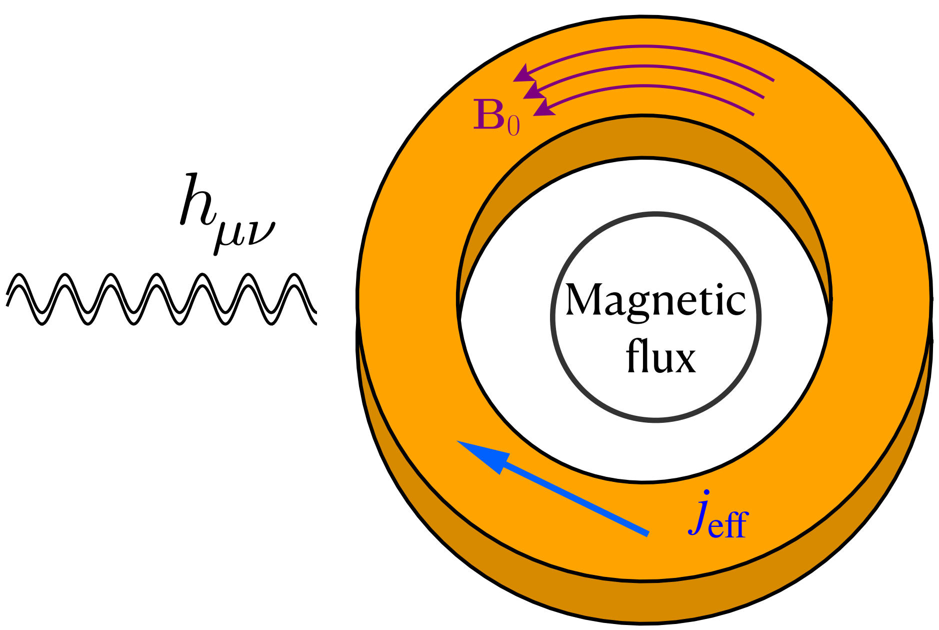
$$\Phi \approx \frac{\mathrm{i}e^{-\mathrm{i}\omega t}}{16\sqrt{2}} h^\times \omega^3 B_{\rm max} \pi r^2 R a(a+2R) s_{\theta_h}^2$$

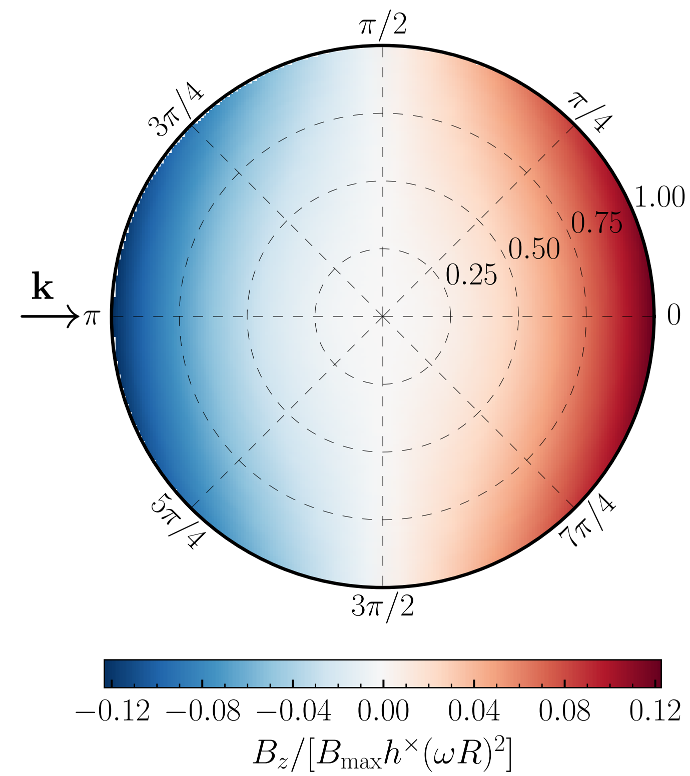
Only one polarization

Suppression at small frequencies

Haloscopes based on lumped-element detectors

Domcke, CGC, Rodd, 2202.00695





$$\Phi \approx \frac{\mathrm{i}e^{-\mathrm{i}\omega t}}{16\sqrt{2}} h^{\times}\omega^3 B_{\max}\pi r^2 R a(a+2R) s_{\theta_h}^2$$

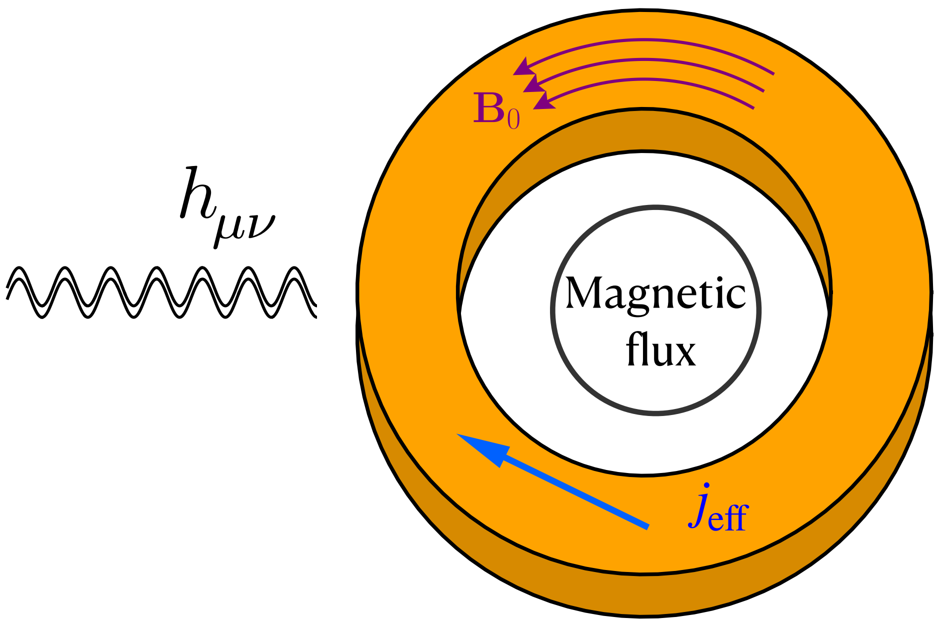
Only one polarization

Suppression at small frequencies

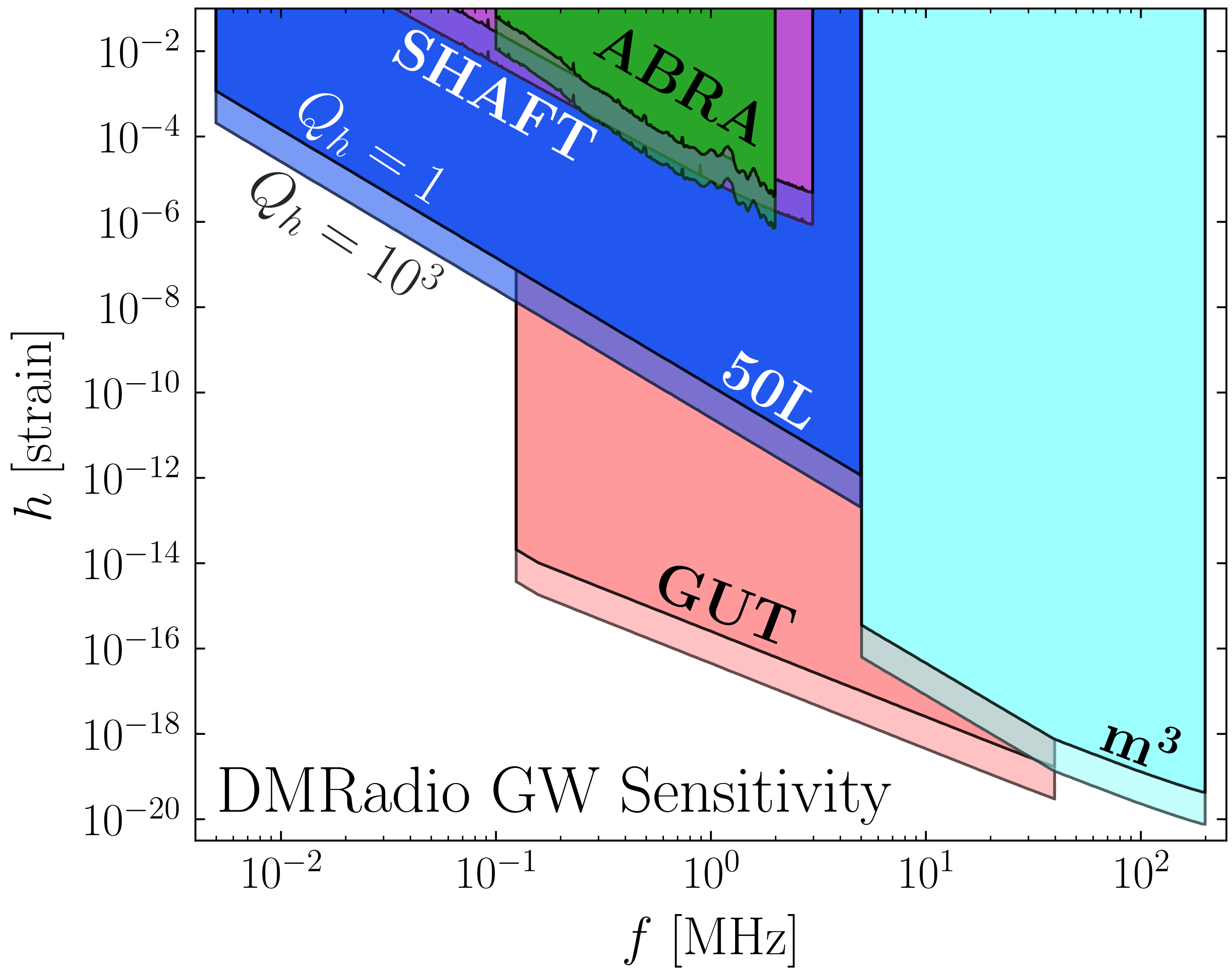
$$\Phi_{\text{axions}} \approx e^{-\mathrm{i}\omega t} g_{a\gamma\gamma}\sqrt{2\rho_{\text{DM}}} B_{\max}\pi r^2 R$$

The sensitivity scaling with the volume is faster than for axions

Haloscopes based on lumped-element detectors



Domcke, CGC, Rodd, 2202.00695



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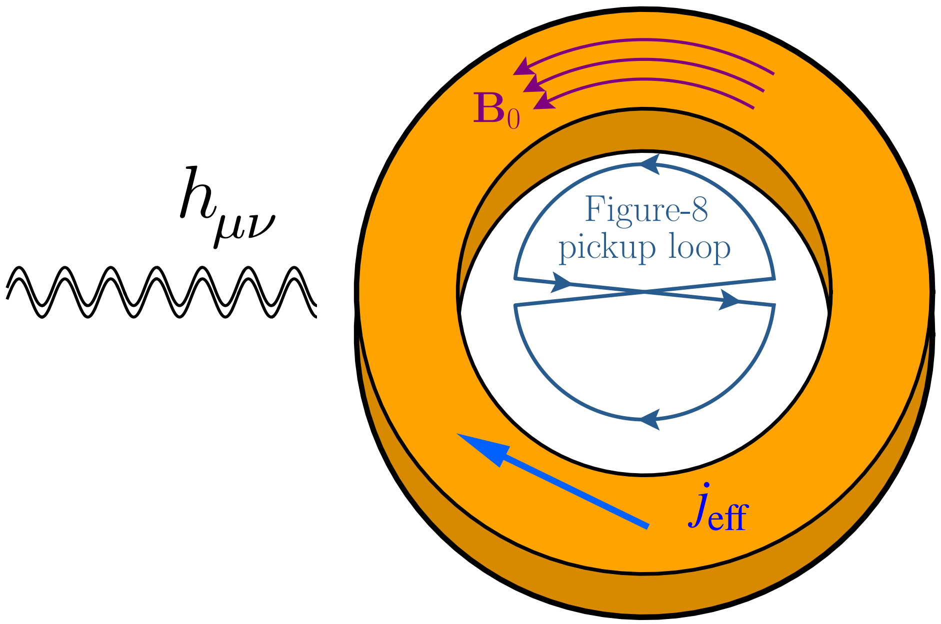
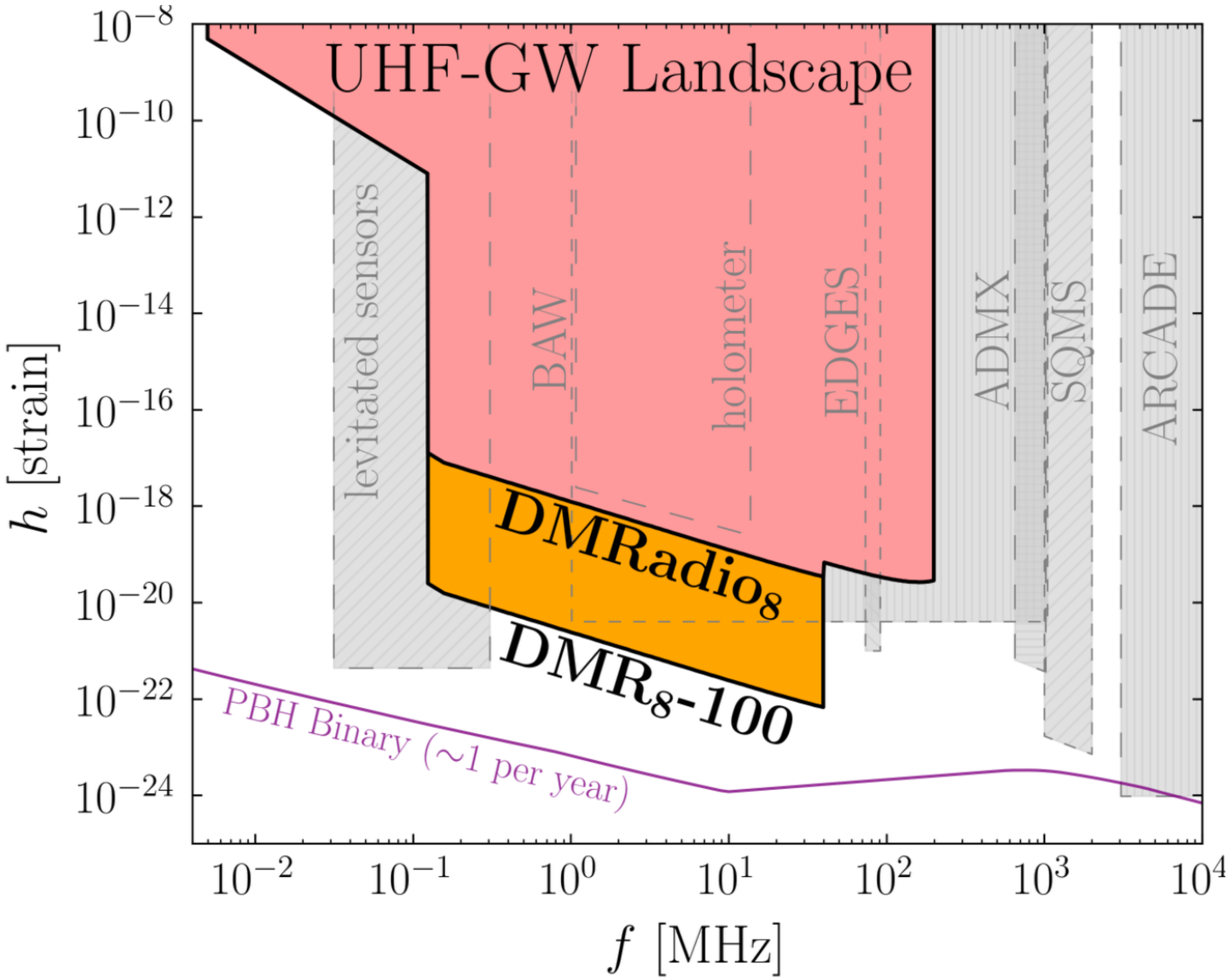
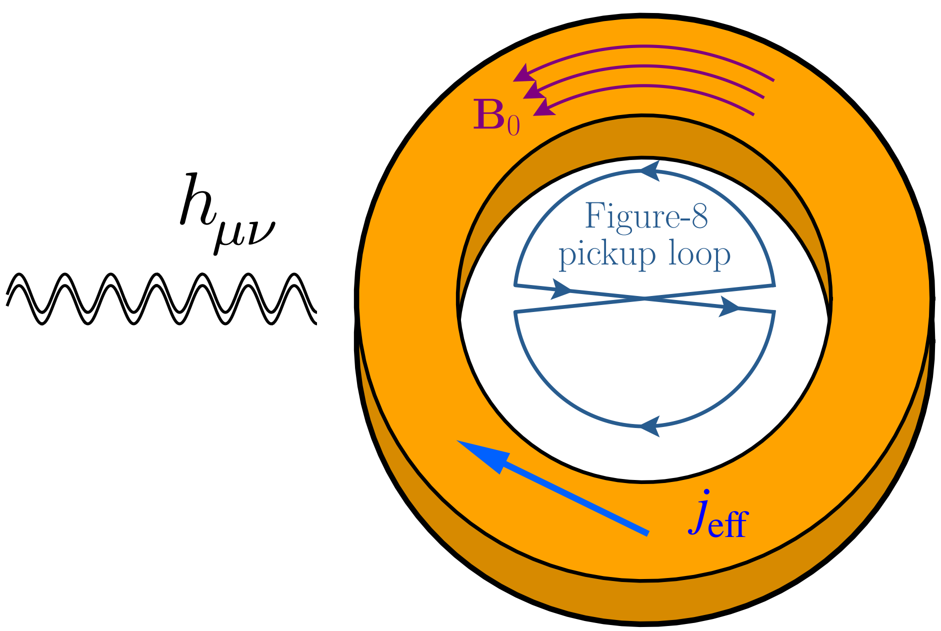
Domcke, CGC, Rodd, 2202.00695



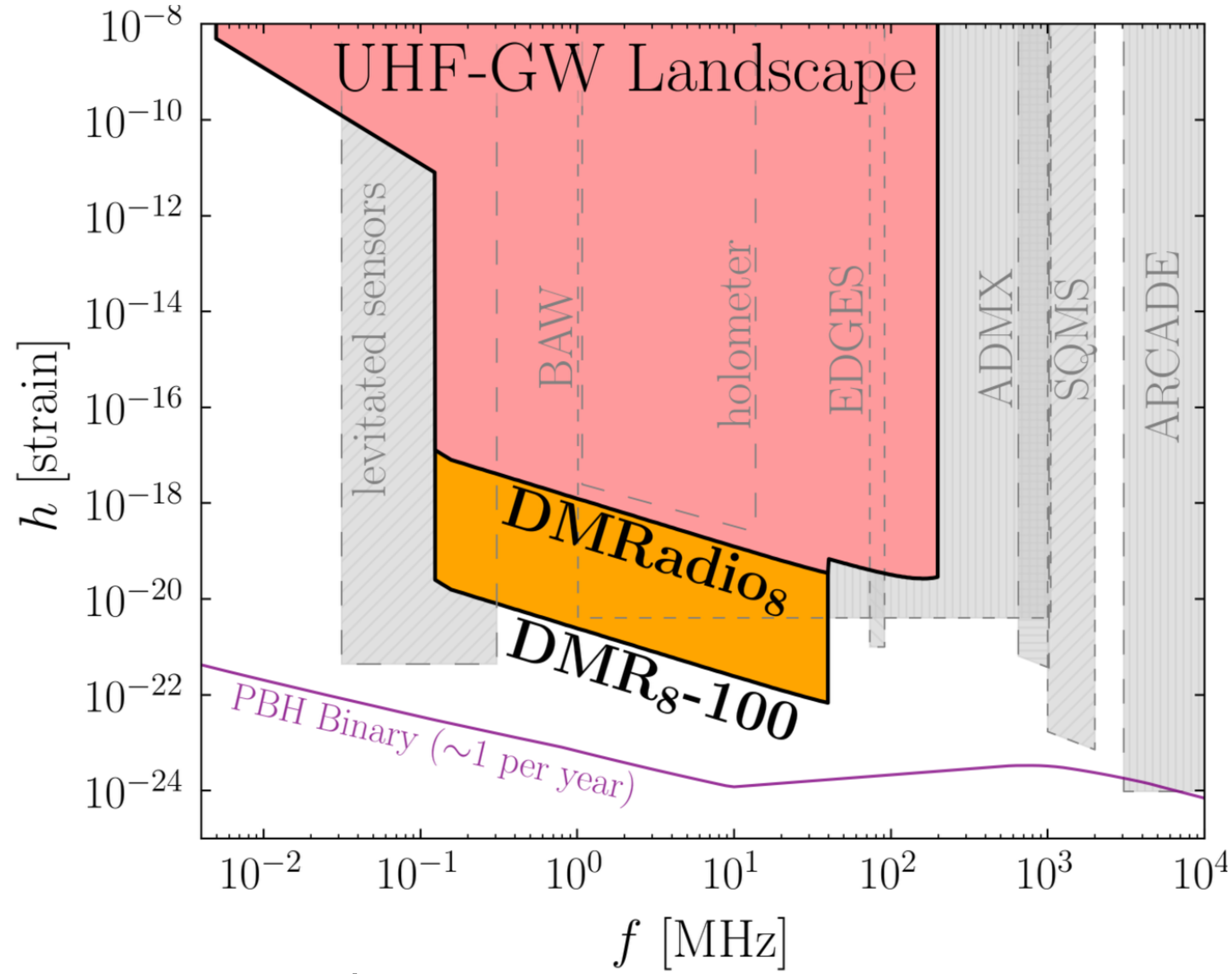


Domcke, CGC, Rodd, 2202.00695

Haloscopes based on lumped-element detectors



Domcke, CGC, Rodd, 2202.00695

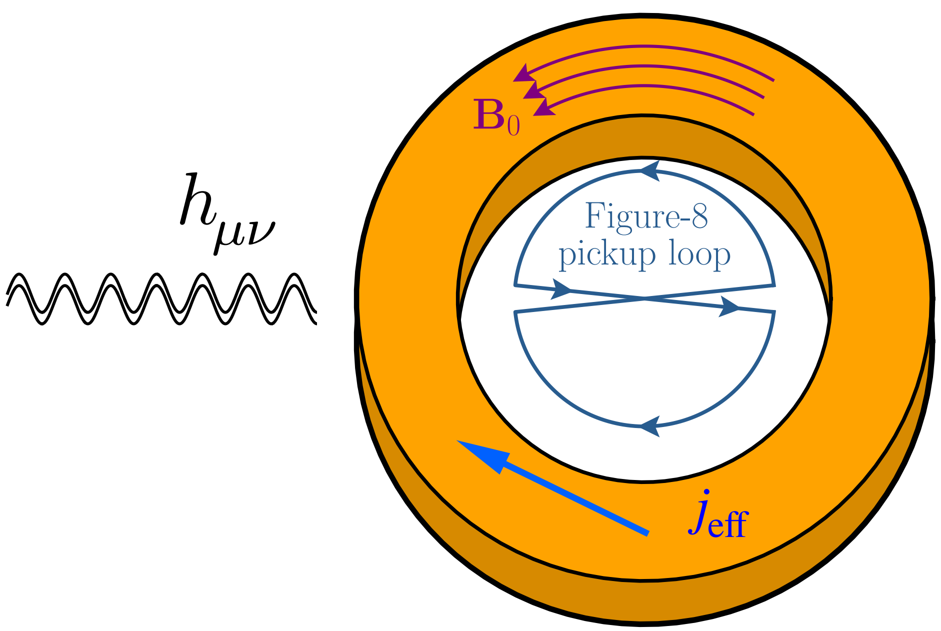


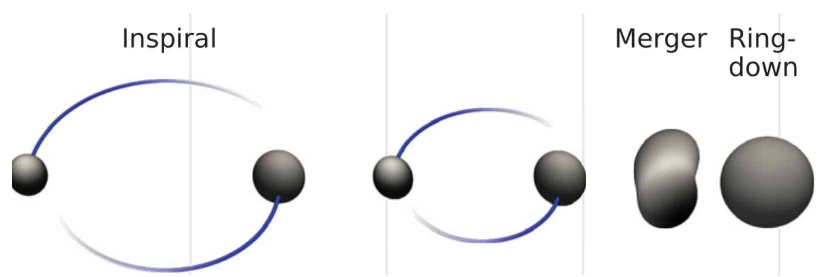
$$\Phi_8 \approx \frac{e^{-i\omega t}}{3\sqrt{2}} \omega^2 B_{\max} r^3 R s_{\theta_h} \left(h^{\times} s_{\phi_h} - h^{+} c_{\theta_h} c_{\phi_h} \right)$$

Domcke, CGC, Rodd, 2202.00695

Small modification allows to measure both polarizations

Haloscopes based on lumped-element detectors

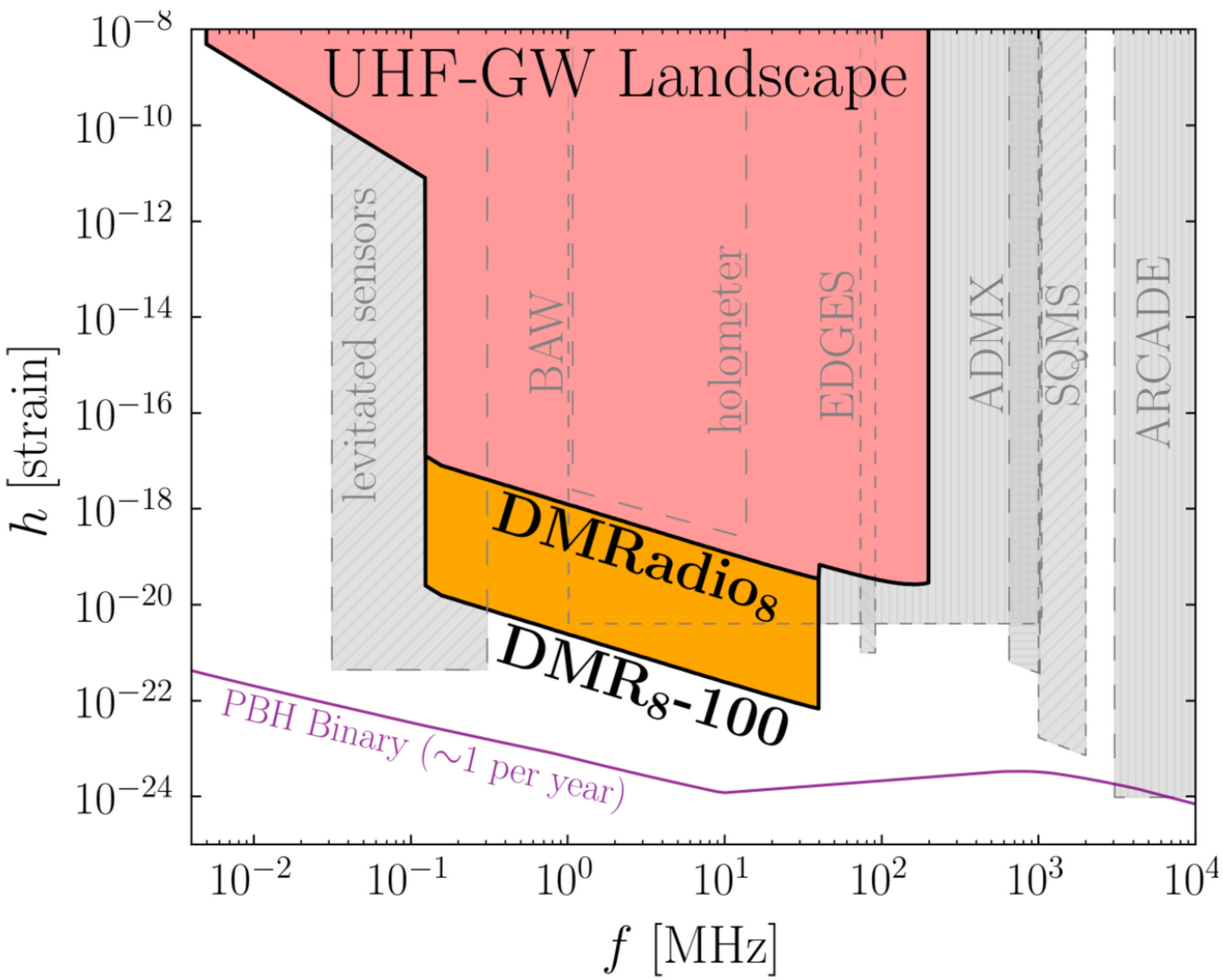




Up-to-date estimate of PBH in binaries
and their expected merger rate accounting
for the local overdensity in the Milky Way

See also 2205.02153 by Franciolini, A. Maharana, and F. Muia,

Domcke, CGC, Rodd, 2202.00695



$$f \simeq 220 \text{ MHz} \left(\frac{10^{-5} M_\odot}{m_{\rm PBH}} \right)$$

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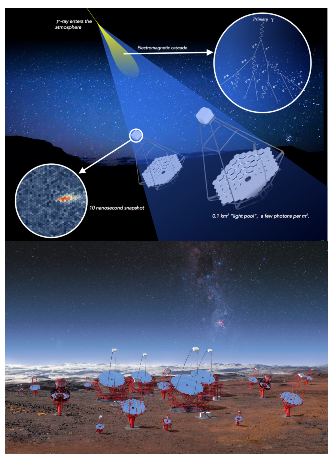
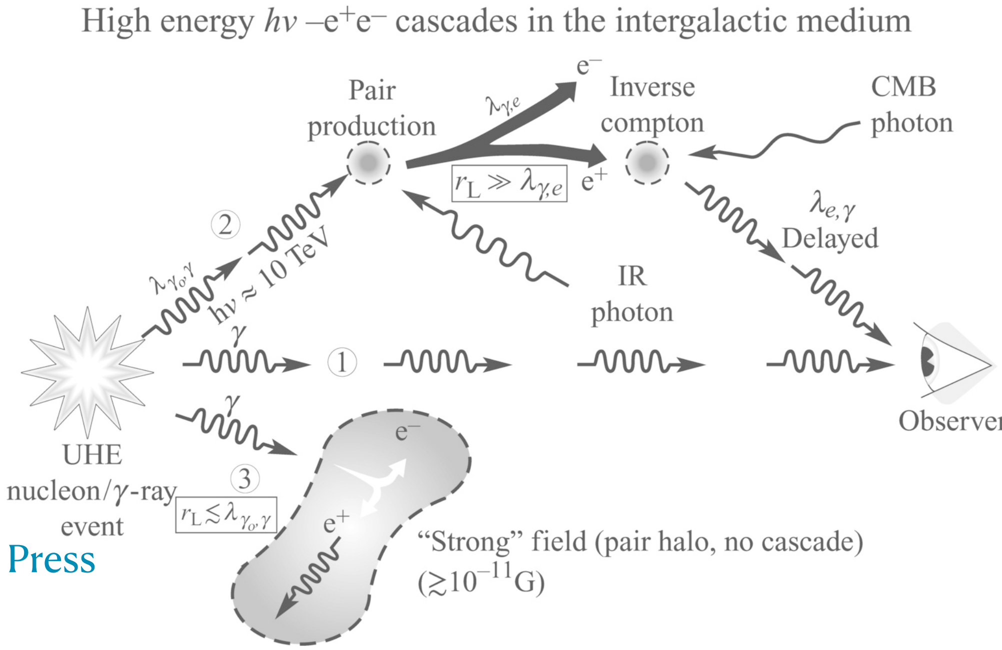
Cosmological detectors

Cosmic magnetic fields

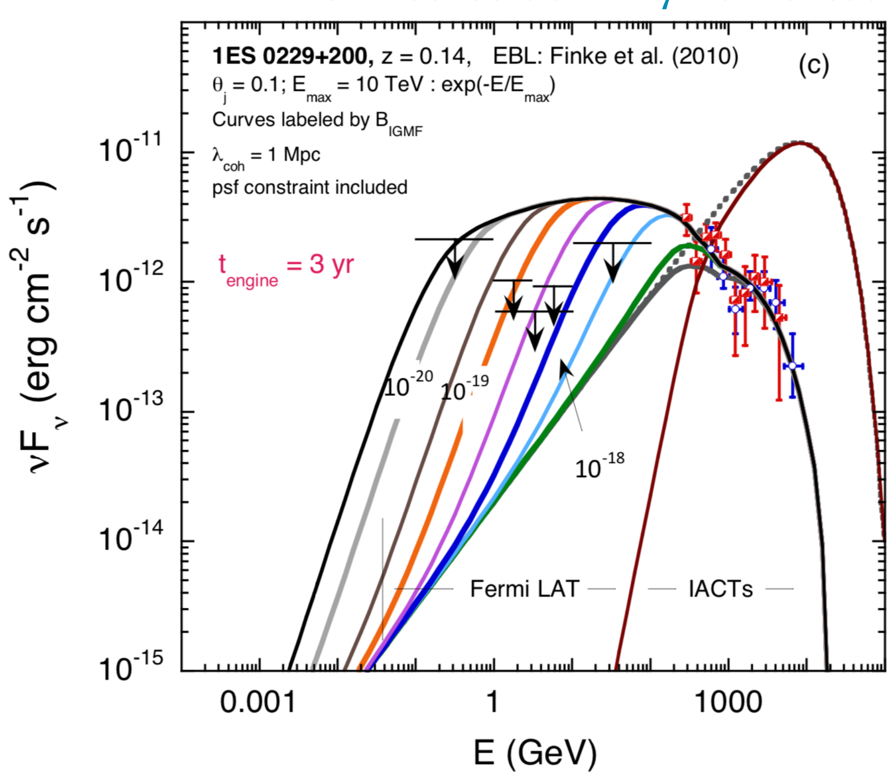
Evidence from TeV Blazars

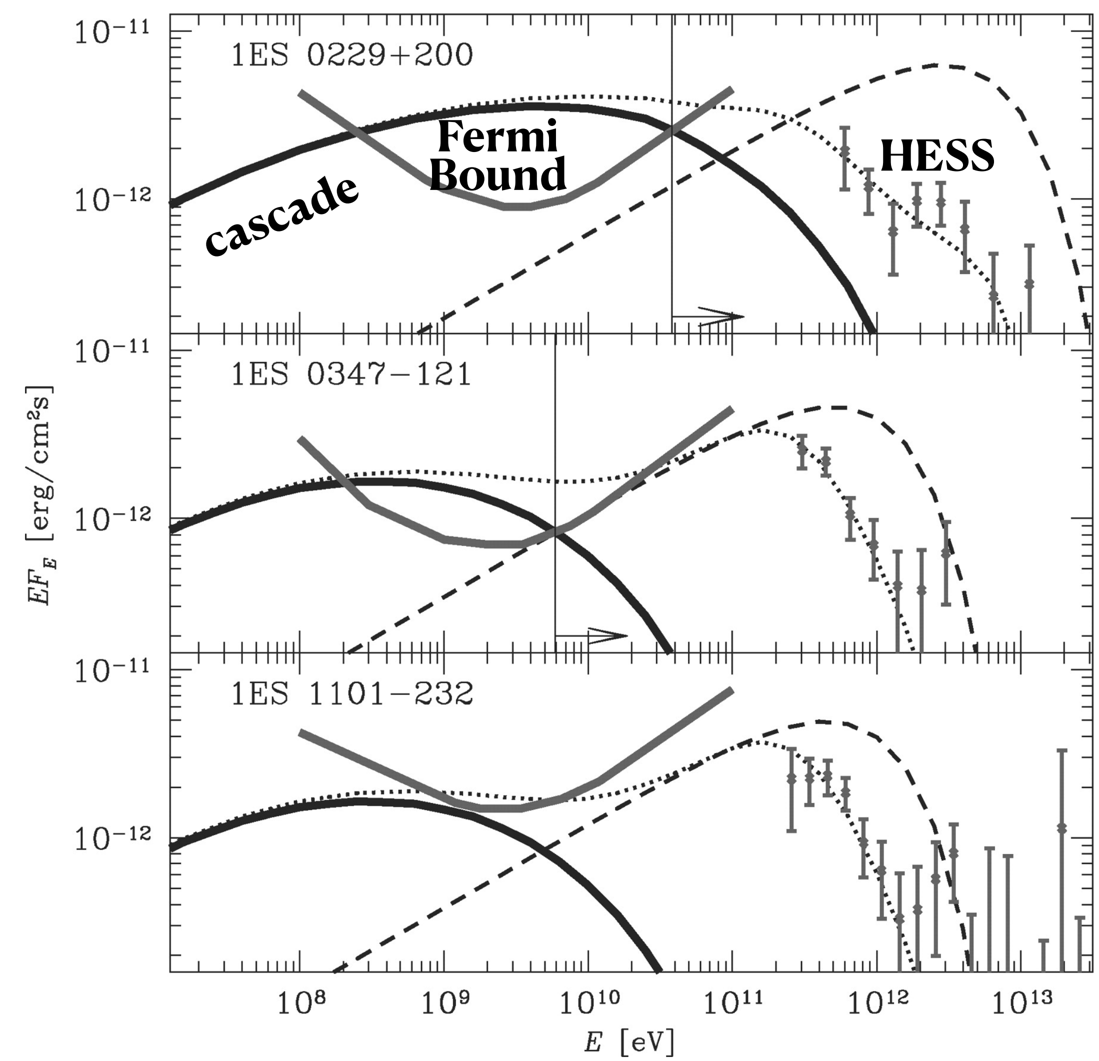


Kronberg , 2016
Cambridge University Press



CTA consortium 2017 Dermer et al





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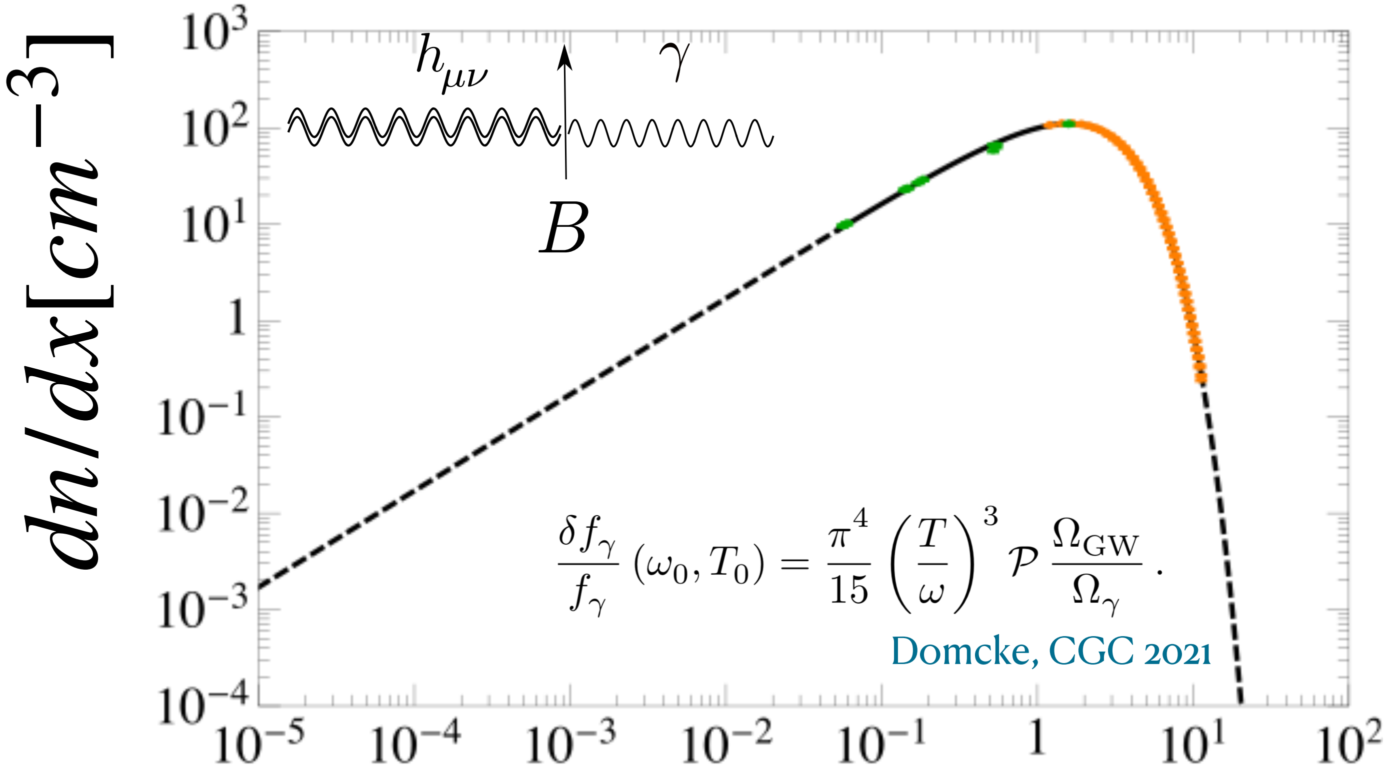
Gravitational Wave conversion during the dark ages



Largely unexplored with upcoming advances in radio astronomy probing it in the near future.

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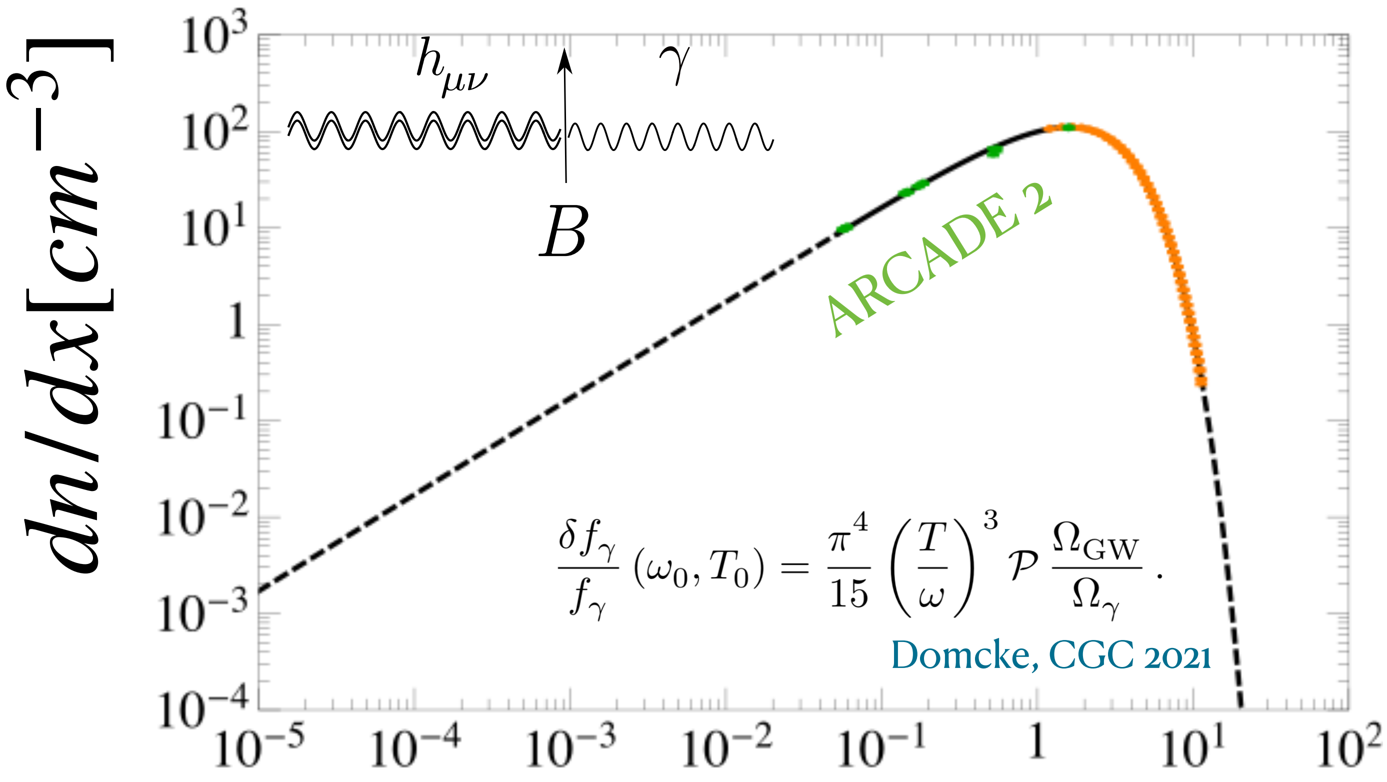

THE ASTROPHYSICAL JOURNAL

ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

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The Astrophysical Journal, Volume 734, Number 1

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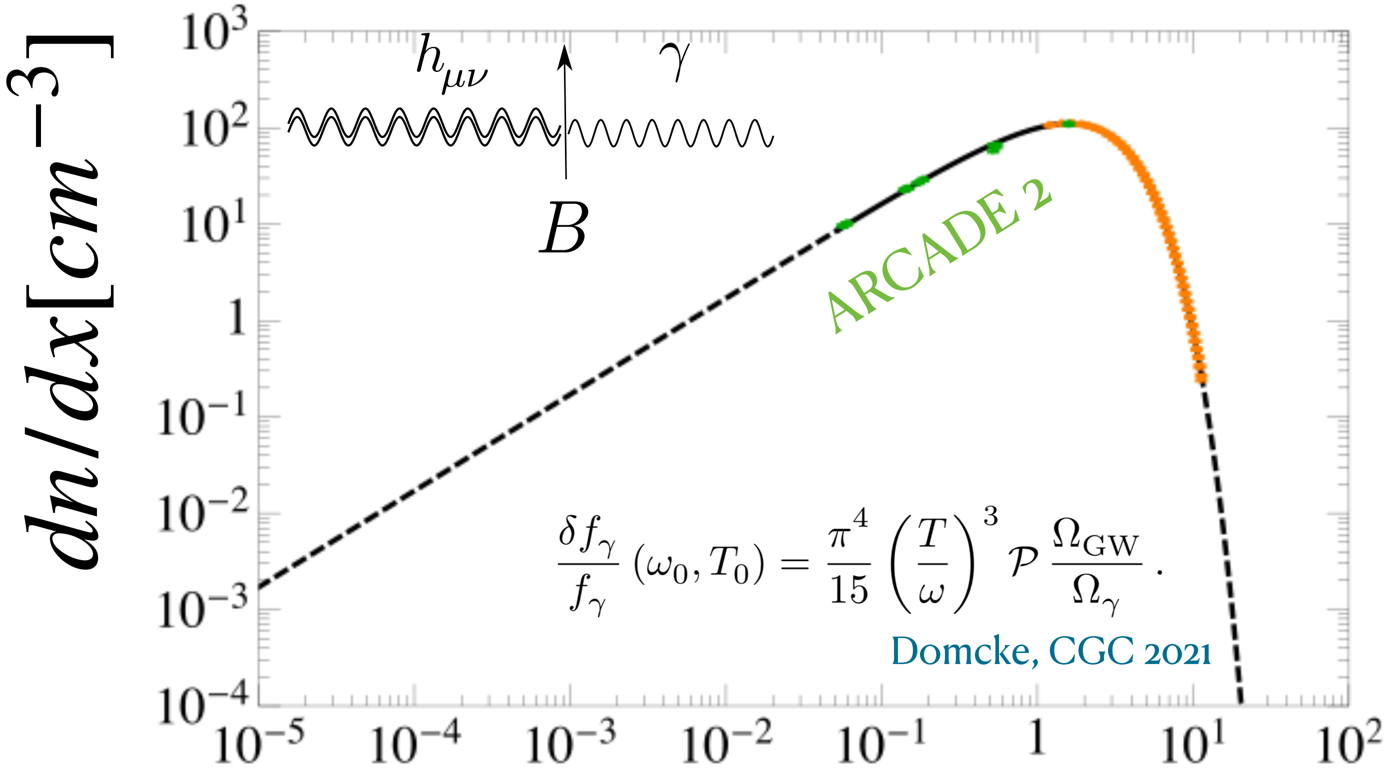

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nature

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

Nature **555**, 67–70(2018) | Cite this article

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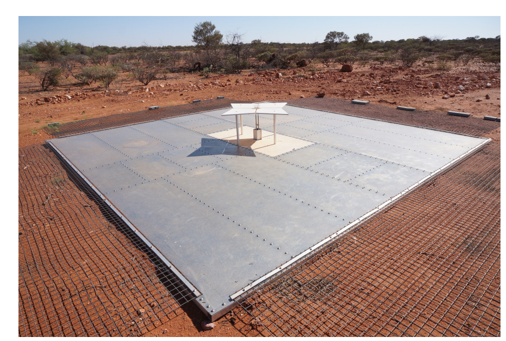
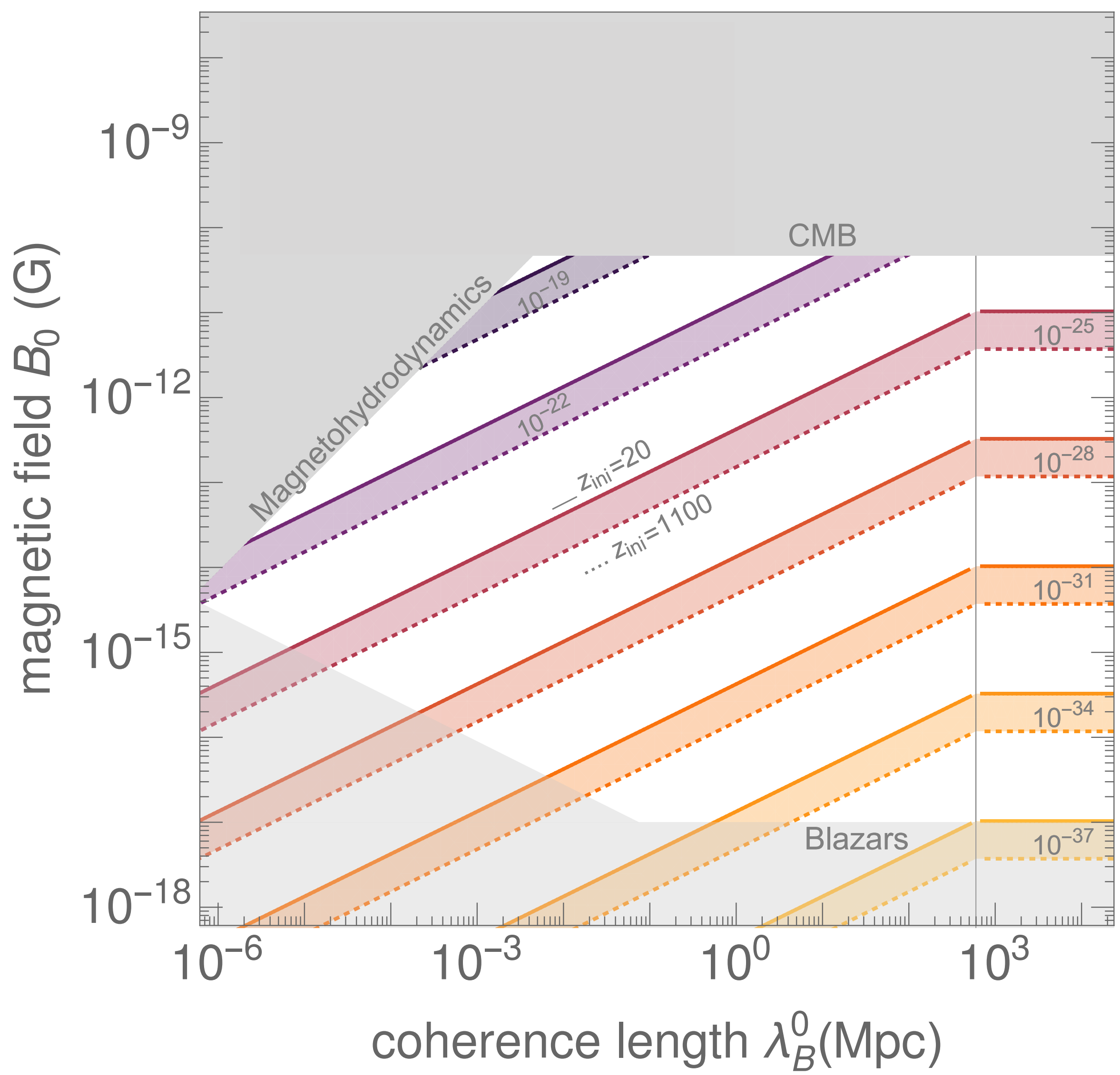
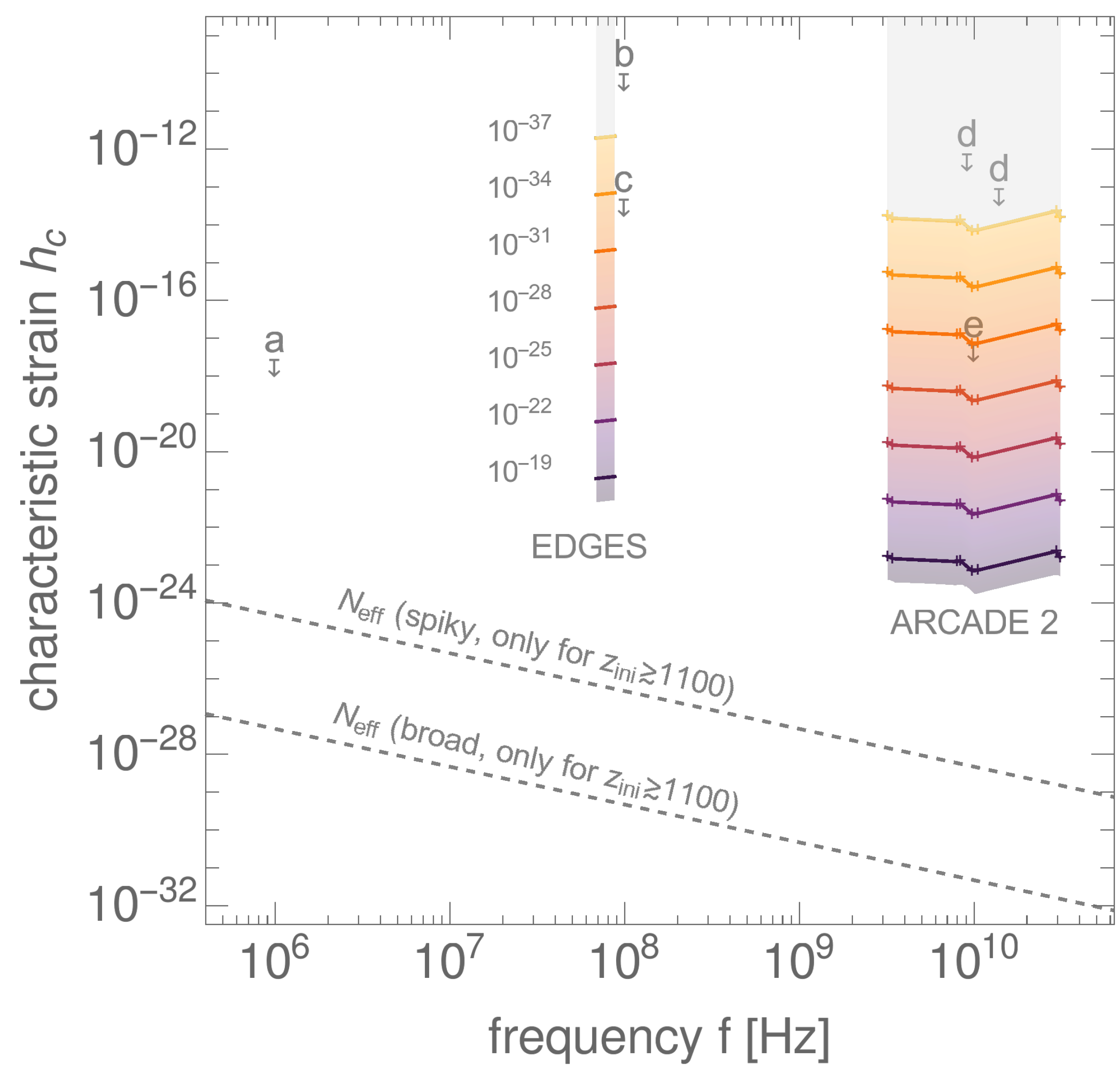


EDGES (Experiment to Detect the Global Epoch of Reionization Signature)

Upper bounds on stochastic gravitational waves





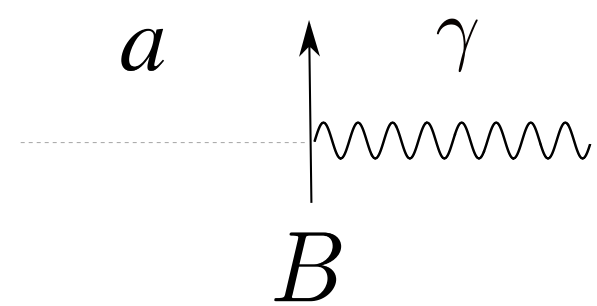
Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

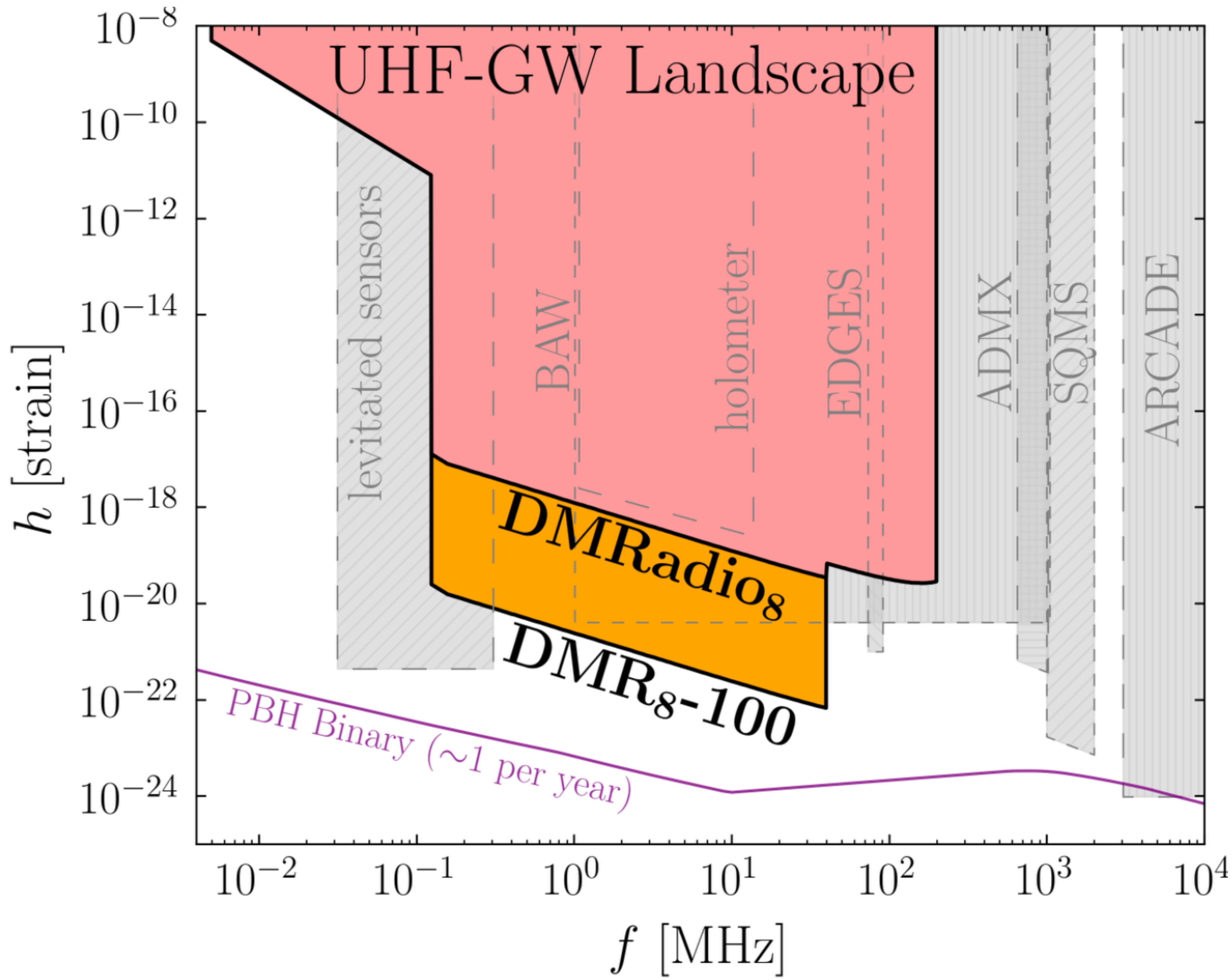
existing laboratory bounds from

a) superconducting parametric converter Reece et al '84
b) waveguide Cruise Ingley '06
c) 0.75 m interferometer Akutsu '08
d) magnon detector Ito, Soda '04
e) magnetic conversion detector Cruise et al '12

Camilo García Cely, University of Valencia

	Axion electrodynamics	Gravitational wave electrodynamics
An example		Gertsenshtein effect
Effective current $j^{\mu}_{\text{eff}} = \left(-\nabla \cdot \mathbf{P}, \nabla \times \mathbf{M} + \partial_t \mathbf{P}\right)$	$\mathbf{P} = g_{a\gamma\gamma} a \mathbf{B}, \quad \mathbf{M} = g_{a\gamma\gamma} a \mathbf{E}$ McAllister et al, 1803.07755 Tobar et al, 1809.01654 Ouellet et al, 1809.10709	$P_i = -h_{ij} E_j \qquad M_i = -h_{ij} B_j$ (in the TT gauge) Domcke, CGC, Rodd, 2202.00695
Benchmark	QCD axion	$h \sim 10^{-22}$

Conclusions



Axion experiments may discover not only dark matter, but also exotic sources of gravitational waves

Different experimental proposals have coalesced on a strain sensitivity of 10^{-22} for MHz GWs, still orders of magnitude away from signals of the early Universe. Whether we can hope to probe such strain sensitivities remains to be determined.

Backup slides

Cosmic magnetic fields

$$\langle \mathbf{B}_i(\mathbf{x})\mathbf{B}_j(\mathbf{x}')\rangle = \frac{1}{(2\pi)^3 a(t)^4}\int d^3k e^{i\mathbf{k}\cdot(\mathbf{x}'-\mathbf{x})}\left(\left(\delta_{ij}-\hat{k}_i\hat{k}_j\right)P_B(k) - i\epsilon_{ijk}\hat{k}_k P_{aB}(k)\right) ,$$

Durrer, Neronov, 2013

The adiabatic evolution of the magnetic field due to cosmic expansion is determined by the scale factor.

$$\langle B^2\rangle = \frac{1}{\pi^2 a(t)^4}\int_0^\infty dk k^2 P_B(k) = \int_{-\infty}^{\infty} d\log\lambda\, B_\lambda^2$$

where $B_\lambda^2 \equiv \frac{8\pi}{\lambda^3 a(t)^4} P_B\left(\frac{2\pi}{\lambda}\right)$,

average magnetic field

$$\lambda_B = \int_0^\infty d\lambda \frac{B_\lambda^2}{\langle B^2\rangle}$$

the coherence length

Oscillations after the formation of the CMB

$$\left(\Box + \omega_{\rm pl}^2\right) A_\lambda = - B\partial_\ell h_\lambda$$

$$\Box\, h_\lambda = 16\pi G B\, \partial_\ell A_\lambda$$

$$\omega_{\rm pl} = \sqrt{e^2 n_e / m_e}$$

The plasma frequency acts as an effective mass term

$$\ell_{\rm osc} \simeq 4\omega / \omega_{\rm pl}^2$$

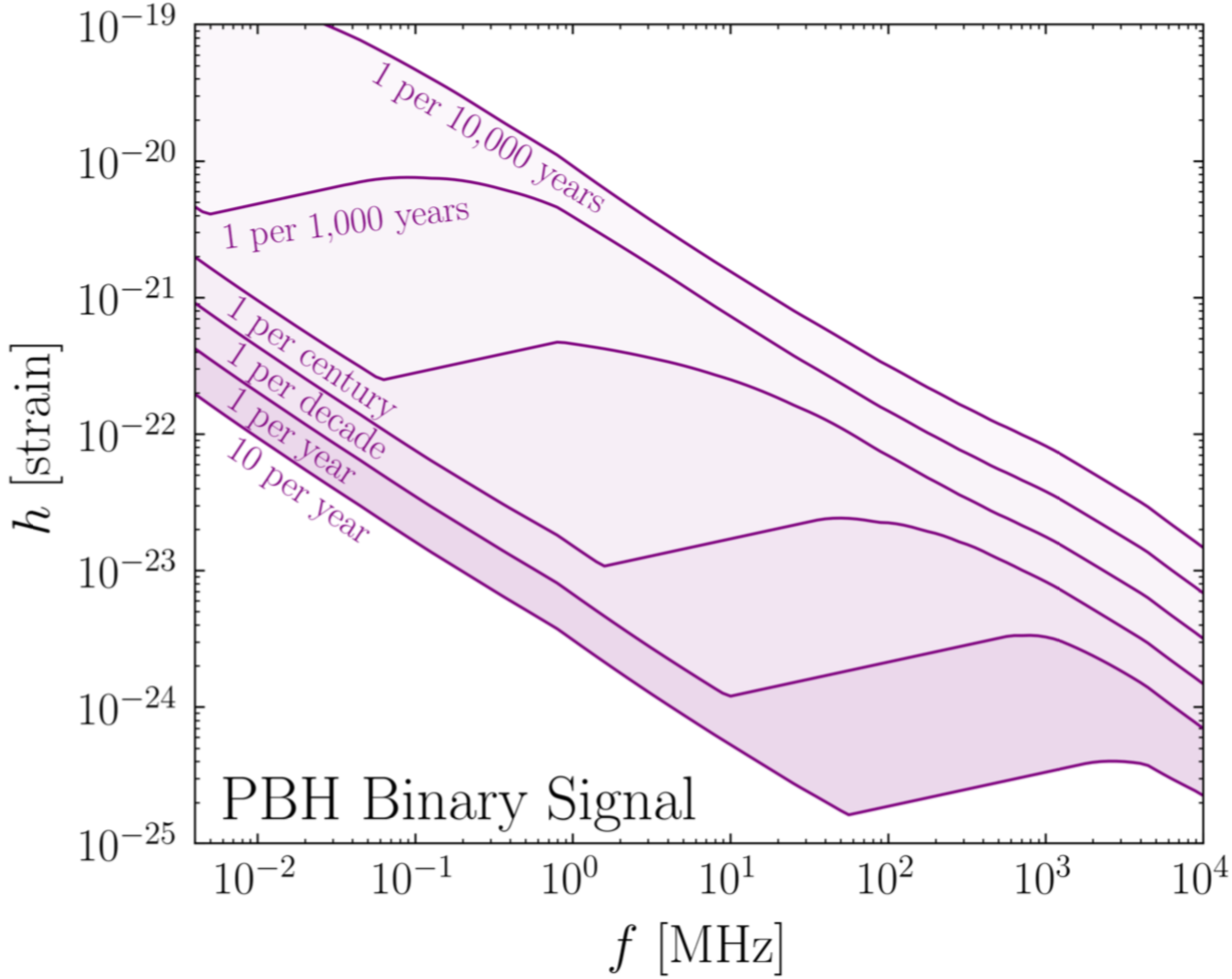
Although cosmic magnetic fields are not expected to be perfectly homogeneous, coherent oscillations take place in highly homogeneous patches.

$$\ell_{\rm osc} = 4\omega/(1+z)^2 X_e(z)\omega_{\rm pl,0}^2 \ll 1\ {\rm pc}$$

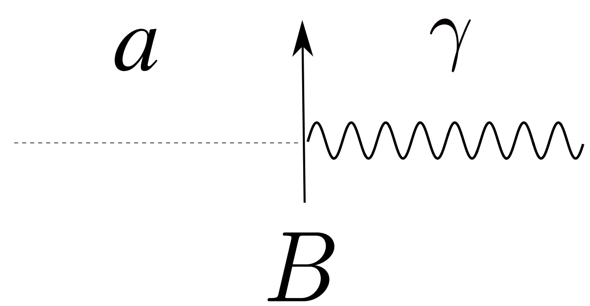
$$\langle \Gamma_{g\leftrightarrow\gamma} \rangle = \frac{2\pi G B^2 \ell_{\rm osc}^2}{\Delta \ell}$$

$$\mathscr{P} \equiv \int_{l.o.s.} \langle \Gamma_{g\leftrightarrow\gamma} \rangle dt = \int_0^{z_{\rm ini}} \frac{\langle \Gamma_{g\leftrightarrow\gamma} \rangle}{(1+z)\, H} dz$$

Domcke, CGC 2021



Camilo García Cely, University of Valencia

	Axion electrodynamics	Gravitational wave electrodynamics
An example		Gertsenshtein effect
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